Dimensioning a passenger, touristic train for ecological and economical performance, and EU gas emission normative compliance, for a regional, non-electrified rail line on mountainous terrain.

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Abstract

Rail lines that have too little traffic to be electrified may face difficulty in adapting the propulsion of their moving railway material to the progressively more stringent regulations on gas emissions. Lasting changes in the relative prices of fuels also affect which types of fuels and engines are most cost-effective. Here we will attempt to establish the bases for evaluating whether the current Diesel-Electric paradigm is becoming outdated, and whether one particular alternative, a gas turbine fuelled by natural gas, is worth switching to. We will be focusing on the specific example of the Lleida-La Pobla rail line, and whether the industrial tissue around it is equipped to facilitate such a change.
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If I’m forgetting anyone, I beg of them that they do not feel slighted or forgotten.
Motivation, Aims, and Scope

Motivation

Here are, in order of immediate practicality, the reasons why I’m making this final thesis:

- To obtain my engineering degree in a timely manner so that I may seek further education or a place in the workforce.
- To establish that I am capable of doing quality research work, and present it in a succinct, high-quality manner.
- To delve deeper into railway technology in preparation for a future in the profession.
- To compile and make this information available to whomever it may be of use to.
- To make a valuable contribution to current knowledge in the field, however small it may be.
- To satisfy my personal curiosity regarding the viability of Natural Gas as a rail fuel and of gas turbines as a rail propulsion technology.
- Assuming the results are favourable to said technology, to encourage progress in that direction.
- To help towards the technological and economical upgrades of the Lleida region, especially in the Segre valley constituencies, which have been in an economic slump for a long time, and to whom a historical and economical debt is owed.

Aims

This project aims to establish whether it would be viable to replace the present, Diesel propulsion system of the Lleida-La Pobla train with a system relying on Natural Gas for propulsion, all the while exploring additional approaches, technological and not, for the sake of improving the service’s economical, ecological and social viability, and helping guarantee is perennity for the benefit of the public.

Scope

This paper intends to provide a general overview of the current state of the Lleida-La Pobla rail line, and the rolling material that circulates in it. Reasons for reform, technological and otherwise, are justified, and one particular alternative, the retrofitting of previously existing rail vehicles with natural-gas-fuelled gas turbines for power generation, is considered in some detail: from its history, to the state of the art, to future opportunities. Some foundations towards the development of a mathematical model of the train’s behaviour, to be built upon by future researchers.
Contents

1 Context

1.1 The line: The Lleida-La Pobla line ........................................ 15
  1.1.1 Technical details .................................................... 15
  1.1.2 Stops .................................................................. 16

1.2 Topographical Data .............................................................. 16
  1.2.1 Mobile Materials ...................................................... 17
  1.2.2 History .................................................................. 17
  1.2.3 Future plans ............................................................. 18
  1.2.4 Applicability to other non-electrified lines ..................... 19
  1.2.5 Conclusions .............................................................. 19

1.3 Technological precedent: Turbo-Trains ................................... 19
  1.3.1 Switzerland .............................................................. 19
  1.3.2 France .................................................................. 20
  1.3.3 UK ..................................................................... 21
  1.3.4 North America ........................................................ 21
  1.3.5 Russia/USSR ........................................................... 23
  1.3.6 Other Countries ........................................................ 23
  1.3.7 Steam Turbine Trains ................................................ 23
  1.3.8 Conclusions .............................................................. 23
2 The Current Conjuncture

2.1 The suitability of electrification .............................................. 25

2.2 Tightening EU gas emission standards ..................................... 26

   2.2.1 Other Provisions .......................................................... 27

   2.2.2 Test Cycle ................................................................. 27

2.3 CO2 Emissions to be Expected .............................................. 28

2.4 The suitability and cost-effectiveness of natural gas .................... 28

   2.4.1 Suitability regarding emissions ....................................... 28

   2.4.2 The Cost-Effectiveness of Gas Prices ............................... 29

   2.4.3 Future Projections of Gas Prices: Relative Economical Advantages 29

   2.4.4 Challenges ............................................................... 30

   2.4.5 Conclusion ............................................................... 31

2.5 The suitability of gas turbines .............................................. 31

   2.5.1 The Pier Study ........................................................... 32

   2.5.2 Conclusions ............................................................... 36

2.6 Available Infrastructures ..................................................... 36

   2.6.1 Natural Gas Logistics ................................................... 36

   2.6.2 Cogeneration and Electrogenic Groups ............................. 37

   2.6.3 Rolling Stock Manufacturers ......................................... 40

2.7 Possible further improvements .............................................. 42

   2.7.1 Improving Energy Efficiency ......................................... 42

   2.7.2 Environmental and Social Impact ................................... 45

3 Decisions .............................................................................. 49

Glossary ................................................................................. 50

Bibliography .......................................................................... 55

Appendices ............................................................................ 59
CONTENTS

A Calculations and Modeling 61

A.1 Data setting and extraction ........................................ 61

A.1.1 The railway ........................................ 61

A.2 Power requirements ........................................ 62

A.2.1 Train Resistance and tractive efforts ......................... 62

A.3 Control And Drives ........................................ 65

A.3.1 Power ........................................ 65

A.3.2 Speed Limitations ........................................ 65

A.4 Some gross estimations ........................................ 65

B Budget 69

C Tables and Maps 71
List of Figures

2.1 Brent Crude vs. Henry Hub prices .................................................. 30
2.2 Railroad Diesel vs. LNG prices ...................................................... 31
2.3 Long-term Fuel-Cost savings .......................................................... 32
2.4 Net Present Value of LNG locomotives .............................................. 33
2.5 Power vs. speed, by notches .......................................................... 35
2.6 Frequency of notch positions .......................................................... 36
2.7 Power vs. emissions of typical Diesel engine, and turbines with and without recuperation and adjustment .................................................. 36
2.8 Power vs. inlet temperature of TF15 .................................................. 37
2.9 Emissions per trip for each solution .................................................. 37
2.10 Fuel consumption for each configuration ......................................... 38
2.11 Comparison the emissions per trip for the diesel locomotive LNG conversion and the diesel#2 fueled TF15 locomotive .................................................. 38
2.12 Comparison the emissions per trip for three different combinations ........ 39
2.13 Power vs. inlet temperature of C200 ................................................. 39
2.14 Efficiency vs. power of C600 ......................................................... 40
2.15 Efficiency vs. power of C800 ......................................................... 40
2.16 Efficiency vs. power of C1000 ......................................................... 41
2.17 Top view of Capston’s Clean Cycle 125kW engine ............................ 44
2.18 Photograph of Capston’s Clean Cycle 125kW engine .......................... 44

A.1 Obtaining the data from position $x$ in Simulink ................................. 62
A.2 $w_c$ from $R$ in Simulink ............................................. 62
A.3 $F$ from $w$ in Simulink .................................................. 63
A.4 $w_r$ in Simulink .............................................................. 63
A.5 $w_g$ from $s$ in Simulink .................................................. 64
A.6 $w_c$ from $R$ in Simulink .................................................. 64
A.7 $v$ and $x$ derived from $a$ .................................................. 65
A.8 $w_g$ from $s$ in Simulink .................................................. 66
A.9 Speed limits throughout the Lleida-La Pobla line, pt. I ........... 66
A.10 Speed limits throughout the Lleida-La Pobla line, pt. II .......... 67
List of Tables

1.1  Data on the powering and braking systems of gas turbine trains throughout history 24

2.1  European Emission Standards for Rail Traction Engines .......................... 27

2.2  Emissions Test Cycle F for Locomotives on ISO 8178 ............................ 28

2.3  Emission rates of rail vehicles depending on type of service ..................... 28

2.4  CO2 emission rates by type of fuel ....................................................... 28

2.5  Comparison between trains ................................................................. 34

2.6  Common characteristics of all Capston electrogenic groups ....................... 41

2.7  Specific characteristics of all Capston electrogenic groups ....................... 42

2.8  Technical sheet of the Capstone Clean Cycle 125kW Waste Heat to Electricity Generator .......................................................... 47

B.1  Rough estimation of the project’s cost ................................................. 69
Chapter 1

Context

In this chapter, we will review the line of Lleida-La Pobla and its current characteristics and past history, as well as the technology of Turbo-Trains, and we will attempt to find out why they have remained a marginal rail technology until now.

1.1 The line: The Lleida-La Pobla line

The Lleida-LaPobla rail line, or line Ca7, connects both municipalities since 1951. The infrastructure belongs to Ferrocarrils de la Generalitat (FGC), the Catalan Generalitat’s rail operator since 2005. 70% of users are concentrated in the segment between Lleida and Balaguer, with the rest of the line until La Pobla serving a more touristic function. It takes 1h and 50min to travel the whole distance.[32]

1.1.1 Technical details

Based on the maps provided by the Generalitat[59][58]:

- Length: 89.35 km of rail, unelectrified.
- Rail gauge: 1.668 mm or ibérian gauge.
- Stops: 17.
- Tunnels: 41.
- Longest tunnel: Palau, with 3499 m under the Serra del Mont-roig.
- Bridges: 31.
- Longest bridge: over the Segre en Balaguer, 160 m long.
- Crossings: 21.
- Type of blocking: telephonic.
1.1.2 Stops

There are 17 stops\textsuperscript{[60]}:

- Alcoletge
- Vilanova de la Barca
- Tèrmens
- Vallfogona de Balaguer\textsuperscript{*}
- Balaguer
- Gerb\textsuperscript{*}
- Sant Llorenç de Montgai
- Santa Linya\textsuperscript{*}
- Vilanova de la Sal
- Àger
- Cellers-Llimiana
- Guàrdia de Tremp\textsuperscript{*}
- Palau de Noguera\textsuperscript{*}
- Tremp
- Salàs de Pallars\textsuperscript{*}
- La Pobla de Segur

\textsuperscript{*} These stops are optional and it takes an advance notice to the on-board personnel for the train to stop there.

1.2 Topographical Data

Several sources offer relevant topographical data regarding the rail line and its surroundings: ordnance survey maps, cadastral registration maps, maps of the councils, maps of the electrical network, and maps of the railway itself contain information from which we can deduce the data we need. In particular, Ferrocarrils de la Generalitat de Catalunya (FGC) have been kind enough to volunteer detailed maps of the rail line\textsuperscript{[59]}\textsuperscript{[58]}, for the stretch between Lleida and Blaguer and the one between Balaguer and La Pobla de Segur. These contained a highly detailed account of:

- degree of steepness/slope/ramping
- radius of curvature/bend radius
- the beginnings and endings of tunnel stretches
- the precise location of every train stop along the rail line

We have transcribed all of this information to digital format, assigning an approximate, constant value for each of these variables for every 20m stretch of rail line. The digital simulation of the train’s needs was based on this data. The tables may be consulted in the annex (See Table ??)
1.2.1 Mobile Materials

1.2.1.1 Usual transport

These self-propelled units are subcontracted as a service by FGC from Renfe.[32][33]

- Diesel unit, Renfe series 592.2, a.k.a. 'Superman'; 200 seats in three cars, top speed 140 km/h.
- Diesel unit, Renfe series 596, a.k.a. 'Tamagotxi'; 56 seats in one single car, top speed 120 km/h.
- Formerly: diésel unit, Renfe series 593, 'Camello'.

1.2.1.2 Tourist transport

The Associació per a la Reconstrucció i Posta en Servei de Material Ferroviari Històric (ARMF) manages special trips with historical, preserved materials, including the regular touristic services of the tren dels Llacs.[32][33]

- Diesel locomotives 10.817 and 10.820, popularly known as 'Yeye'.
- Steam locomotive 282F-0421, popularly known as 'Garrafeta'.

1.2.2 History

The stretch between Lleida Pirineos and La Pobla de Segur was intended to be part of an international line of 850 km, from the andalusian Baeza to the southern French village of Sent Gironç, through Albacete, Utiel, and Teruel, within the context of the 1926 'Guadalhorce' Urgent Railway Construction Plan of the Primo de Rivera’s regime, with the purpose of improving communications between France and the Iberian Peninsula. The plan was put on hiatus during the Second Spanish Republic and the Civil War, and resumed during the Franco dictatorship under the new state railway company Red nacional de ferrocarriles españoles (Renfe). So the train would reach Cellers in 1949, Tremp in 1950 and La Pobla de Segur on November 13 of 1951.[44]

The year 1962, on the recommendation of the World Bank, the Spanish government decided to stop the construction of new rail lines and focus on improving those already operational. The 'Guadalhorce' plan was abandoned, as the Northern connection with France was already covered by the already operational Canfranc and Puigcerdà. Consequently, although the ground had already been flattened to extend it to Sort, the line terminated in La Pobla de Segur.[45]

During the '60s and '70s, private vehicles became increasingly affordable for family economies in Spain, and went through a surge in popularity. Simultaneously, there was a gradual depopulation of rural areas as the Pyrenees. Rail transport took a backseat to automobile transportation, both in terms of public demand and in terms of government investment.
CHAPTER 1. CONTEXT

In the '80s, the new government of Felipe González prioritised Spain’s joined the European Economic Community (EEC). One of the measures taken to achieve the required economic health to access to the EEC was the establishment in 1984 of a "contract-program" obliging Red nacional de ferrocarriles españoles (Renfe) to streamline costs in order to remain subsidised. One of the clauses of the contract mandated that, by January 1 of 1985, all lines considered "highly deficient" should be closed; those that could generate less than 23% of their costs in revenue. The State government, county councils and other local authorities could avoid closing such lines under their jurisdiction, as long as they shouldered the cost themselves.

One such line was that of La Pobla, which owes its survival to the strong public support for its continuation. There was a long political struggle between the Catalan government and the state government to transfer the line’s management from the latter to the former. The central government under socialist government led by Prime Minister Felipe Gonzalez and later Popular Party Prime Minister Aznar demanded financial compensation (about 1000 million Pesetas) for the transfer, which the Catalans deemed unacceptable, since the poor condition of the the line required a substantial financial investment.

Finally, the government of José Luis Rodríguez Zapatero agreed in 2004 the free transfer of the line to the Generalitat, which became effective as of January 1 of 2005. Under the terms of the agreement, the Catalan government owned the whole infrastructure from 1,927 km to La Pobla de Segur. Meanwhile, Ferrocarrils de la Generalitat de Catalunya (FGC) and Renfe signed an agreement according to which the state agency is responsible for managing the line and provide rolling stock, as the Catalan company does not have a suitable stable of rolling material.

One of the first measures taken by the Government to revitalise the line was to renew the stretch from Balaguer to La Pobla de Segur which was the one in the worst shape. The Balaguer - Lleida Pirineos stretch had been renovated in 2002 with second hand line from the Barcelona - Puigcerdà - Latour-de-Carol-Enveitg line. The renovation works, with a budget of 60 million euros, were launched in June 2005, and were completed within the year, after which the journey took only one hour and fifty minutes, about ten minutes less than it took before the remodel.

In 2006 Renfe Operator replaced the circulating rolling material, and reformed the Series 592.2 and 596 trains, which has allowed it to maintain a frequency of three trains per day, between the capital and La Pobla de Segur.

The line has considerably increased its passenger numbers since it was acquired by FGC, which aims to provide a commuter service between Lleida Pyrenees and Balaguer and enhance the tourist side of the section Balaguer - La Pobla de Segur. There was a strong drive towards the creation of a core rail commute in the area of Lleida, supported by local institutions and political groups, should increase the frequency of trains between the capital Leida and Balaguer. Within that context, since April 2008, tariff integration was instituted in the Lleida Pyrenees - Balaguer line, which allows free transfer between the train and the various city and intercity buses operating in the valley of the Segre.

In June 2012, the Catalan governmnent approved the acquisition of two trains for a total cost of 9.4 M€, with the purpose of allowing FGC to control the line without Renfe’s contribution.

1.2.3 Future plans

In the longer term, there are discussions of a possible extension of the studied line, which would come to Sort, and thence to Espot and France, or to La Seu d’Urgell, and thence to Andorra.
1.2.4 Applicability to other non-electrified lines

The Lleida-La Pobla line is the only section of railway in Catalonia which isn’t electrified, and thus it is the only one in which the contributions of the present study can be significant. However, given that it is an Iberian gauge rail, the technological developments here discussed may be directly applied to other non-electrified stretches in the peninsula.

It is worth noting that some of those stretches are out of service, even as their rails remain in good condition. Many such stretches are recoverable, especially in some sections with touristic interest. One example of unused stretch of railway would be the railway environment of the "Pinar Grande" station[42], in the Soria province. That location is where the shots of the film "Doctor Zhivago" depicting the deportation to Siberia were taken[41][40]. Said scenes may represent a testimony to the aesthetic value of the area, and its potential touristic attractiveness.[40]

1.2.5 Conclusions

The Lleida-La Pobla line consists of two distinct segments: Lleida-Balaguer is a well-used, proximity commuter service, while Balaguer-La Pobla is a seldom-used, mostly-touristic line.

1.3 Technological precedent: Turbo-Trains

In this section, we will have a look at the previous examples of gas and vapour turbine trains, examine their reported performance, the reasons they were discontinued, and attempt to extract lessons relevant to our current attempt to use this technology.

A summary of all technical data found on the relevant trains is in Table 1.1.

1.3.1 Switzerland

1.3.1.1 SBB-CFF-FFS Am 4/6 1101

Produced by Brown, Boveri & Cie by other of the Swiss Federal Rail Lines, this locomotive was one of the very first of its kind. Because of its relatively low top efficiency of 18% (compared to conventional Diesel engines), and the lack of non-electrified lines in the Swiss network, it never entered series-production.

One of the reasons for the turbine’s inefficiency is that the compressor constantly required 4,500 kW, even in idling. There was also the problem of overheating and wearing down the air brakes during long descents. Thus, a unique form of dynamic braking was conceptualised, that addressed both these problems: the electricity generated by the traction motors was converted into heat, shutting down the oil supply to the combustion chamber so that it generated no more power.[12]
1.3.2 France

1.3.2.1 Turbine à Gaz Spéciale

An experimental, prototype train with a Poyaud 6 cylinder Diesel engine using Diesel fuel and a Turmo III C3 turbine using kerosene, it underwent testing from 1967 to 1972. It attained top speeds of 250 km/h. [24]

1.3.2.2 TGV 001

The Train Grande Vitesse 001 was the first prototype of the famous TGV French high-speed trains, as part of a vast research program on high rail speeds, which covered such aspects as traction, vehicle behaviour, aerodynamics, braking and signalling. It consisted of two locomotives with three passenger carriages between them, every carriage sharing one bogie with the next. The locomotives employed Turbomeca Turmo turbines, borrowed from helicopter technology. Each axle was powered by electric motors, increasing the total available tractive power. [25],[26]

Testing started in 1972, achieving in the same year the world speed record for a gas turbine-electric locomotive (318 kph), and ended in 1978. Because of the 1973 Oil Crisis and the resulting change in energetic strategy in France, combustion engines were phased out in the French rail system, in favour of electrification. The TGV 001 never saw commercial use, and the next generations of TGV were all electrified. But this train had two successful heirs: the SNCF Class T 2000 and the Amtrak Turboliner.

1.3.2.3 SNCF Class T 1000: Élément à turbine à gaz

This first-generation turbo-train had a 736 kW Turbomecha Turmo turbine for cruising speed, and a 295 kW Diesel starter engine for speeds up to 30 km/h, both employing Diesel fuel. It could reach a maximum of 180 km/h. It was later replaced by the more powerful T 2000 in certain lines, but seems to still be used to this day on specific lines.[27]

1.3.2.4 SNCF Class T 2000: Rame à turbine à gaz

These second-generation gas turbine train-sets were built by ANF Industrie and put into service in 1972, and were retired at the end of 2004 (the last four "rames" being sold to Iran). They employed 775 kW Turbomecha Turmo III engines with Voith Hydraulic Transmissions to the powered axles, and two auxiliary 300 kW Turbomécha Astazou turbines to power air conditioning and lighting. It was rated for a top continuous speed of 160 km/h. In total, it consumed 0.58 m³/km of Diesel fuel; this high level of consumption, and its lack of flexibility in adapting its capacity, were the main disadvantages of this particular model.

Because of the 1973 oil crisis, production was halted at thirteen train-sets. The second oil crisis in 1979 caused them to be refitted with Turmo XII engines, improving efficiency and increasing power from 775 to 1150 kW. They were progressively phased out by electrified lines and Diesel-Electric machines. By the 1990s, their main advantage was that, in routes that required many reversals, their double-ended cabs allowed to save the considerable time involved to switch the locomotive from one end of the train to the other.

When equipped with active tilting technology, tests have shown this train to be able to attain 220 km/h.
1.3. TECHNOLOGICAL PRECEDENT: TURBO-TRAINS

1.3.3 UK

The UK developed several trains around the turbine concept, but did not see them through. This is partly because of some decisions that turned out to be ill-advised, such as hiring rocket engineers with no previous experience with rail technology to design the APTE. The models released were: British Railways’ 18000 (1949), 18100 (1951), GT3 (1961), and APTE.

1.3.4 North America

1.3.4.1 Blue Goose

The Blue Goose was a type of freight locomotive under Union Pacific introduced during the 50’s. Their cost-effectiveness was due to the fact that they employed Bunker C fuel, a "leftover", high-density petroleum byproduct that found few other uses. At their height the railroad estimated that they powered about 10% of Union Pacific’s freight trains, a much wider use than any other example of this class. As procedures were developed to make that byproduct useful, notably to make plastics, its price increased until these locomotives ceased to be profitable and they were retired from service by 1969.

1.3.4.2 Amtrak Turboliner

The first six models were French RTG, bought from ANF Industrie by Ford Motor Credit and rented out to Amtrak. They were adapted to the US rail by replacing the original couplers and buffers with ones that fit North American norms. Despite their above-standard fuel consumption, they lasted from 1973 well into the 1990’s, with the last train being retired in 2000. From then on, seven more trains were built under license by Rohr Inc., and called RTL.

In 1995 one of the RTL’s was upgraded with new, more efficient, electronically-controlled turbines (and a better interior): this improved RTL-II remained in function until 2002. The last remaining RTL and the RTL-II were sent for reconstruction by Super Steel Schenectady into RTL-III in 2000, but only one train was successfully renovated, reaching 201 km/h on tests. Legal disputes between Amtrak and the state of New York interrupted the renovation and prompted Amtrak to liquidate the remaining trains.[28]

1.3.4.3 United Aircraft Corporation TurboTrain

This early high-speed train operated between 1968 and 1982 in Canada and between 1968 and 1976 in the USA. Each train was double-ended, with articulated carriages sharing bogies, and a power unit at each end. The trains could be linked end-to-end, thus giving the trainset some flexibility regarding capacity.

The turbines were Pratt & Whitney Canada PT6 (also a UAC division) known as the ST6 (Stationary Turbine), downrated from 600 to 300 hp (447 to 224 kW), using a "free turbine" that acts as a torque coupler, thus driving the powered wheels directly.
The power cars had three engine bays on either side of the car and could mount engines in pairs for two to six turbines, depending on the needs of the carrier\[1\], each power car carrying up to $5.77 m^3$ of fuel\[3\]. One dedicated turbine powered an alternator to provide head-end power and passenger comfort. The turbines being much smaller and lighter than the Diesel engines they replaced, the power cars had a lot of free space that was utilised for passenger and driver comfort.

On December 20, 1967, one of the TurboTrains reached $274.9 km/h$. This remains the world speed record for gas turbine-powered rail vehicles.\[4\]. More information may be found at High Speed Rail Canada’s website\[5\].

1.3.4.4 JetTrain

The JetTrain uses a Diesel engine for head-end power and for low speeds, reserving the usage of the turbines to the higher speeds where they would be most efficient. The 400 kg, 3.75 MW Pratt & Whitney Canada PW150 turbine engine is much lighter than 10 t Diesel engines of equivalent power, and so the JetTrain power car would weight 97.5 t, with an unsprung weight per axle of 2.5 t, and with a top speed of 251 km/h. For comparison, the widely-used EMD F40PH diesel-electric locomotive weighs 117.9 t with an axle weight of 3.9 t, a top speed of 177 km/h, and a power output of 2.3 MW.

This low axle weight is the main advantage of using turbine engines for high-speed trains as opposed to Diesel; by reducing the stress on the rails, it permits the usage of pre-existing rails at high speeds without necessitating any additional work on the railbed. Due to its lighter weight and modern engine, the JetTrain has greenhouse gas emissions that are 30% lower than a diesel unit operating at the same speeds. The silencers completely mute the (otherwise very noisy) turbine; in operation, the noise is the same volume as an equivalent electric train.

In 1997, the USA Federal Railroad Administration wanted to build long-distance high-speed trains for regions where traffic was insufficient to make electrification viable. They invested 50/50 with Bombardier to construct the first prototype, which was completed in June 2001, tested in Pueblo, Colorado, in 2002, reaching a maximum speed of 251 km/h, and taken to a tour of potential high-speed sites. By 2004, they were slated for opening service between Orlando and Tampa in Florida in 2009, but funding was denied in a referendum that same year.

Bombardier also tried to obtain funding from the Canadian government for their ViaFast project, which would have upgraded their ViaRail service in the Quebec City - Windsor corridor and considerably shortened travel times between major Canadian cities without requiring the construction of new, ad hoc rail strips.\[6\] Together with the Van Horne institute\[8\] they studied the viability of employing the JetTrain between Alberta and Edmonton. There was also a possibility that it might replace the British, Diesel-electric, 200 km/h HST\[9\]. Nothing came of any of these proposals, and the JetTrain disappeared from Bombardier’s official information sites.

In 2009, the government of the Yucatan State of Mexico announced the construction of a Transpeninsular High-Speed train\[10\], which would run on Diesel fuel at an average speed of 160 km/h; in their discussions with the government, Bombardier proposed the JetTrain as an adequate alternative.

Despite its numerous advantages, and the fact that its construction was as simple as equipping pre-existing Acela electric trains with a turbine-and-alternator power group, the JetTrain’s production was discontinued due to three main reasons:
1.3. TECHNOLOGICAL PRECEDENT: TURBO-TRAINS

- apparent lack of demand, which has been largely a matter of political will
- relatively higher consumption than Diesel engines in the many transitory periods that rail driving demands
- low demand made the custom-made models much more expensive to produce than more common, mass-produced powercar

1.3.5 Russia/USSR

Russia is a land that is a gas exporter, and the local price of gas is low, although it seems its price will become closer to the European average over time[29]. Past instances of turbine-electric trains include the G1-01 (1959), the GP1 (1964), the GEM-10 GTEL and the GT1, introduced in 2007, runs on liquefied natural gas and has a maximum power output of 8,300 kW. [11]

1.3.6 Other Countries

1.3.6.1 Egyptian National Railway

The ENR bought three RTG in 1983: these trains were longer (10 elements, 600 seats) with better aerodynamic design and Turmo XIII turbines, which were later replaced by Makila 1F4. There are still three of them serving the Cairo-Alexandria line.

1.3.6.2 Iranian Railway

IR bought four RTG trains from ANF Industries in 1975. Altitude, heat, and, most of all, sand, caused serious technical problems regarding the line’s maintenance: drastic modifications of the air inlets were performed as a result. They were used from 1974 up until the Iranian Revolution in 1979, upon which they entered hiatus until 1990; they serve the Tehran-Zanjan line to this day.

They also bought the last 5 RTG remaining in France in 2004; some of them were used for spare parts, others served in the Tehran-Maschad line. In 2009 their original turbines were replaced by Volvo Diesel engines.

1.3.7 Steam Turbine Trains

During the first half of the XXth century, there were several attempts to prolong the usage of steam engines by employing turbines rather than pistons. Piston engine requires many stages and a high level of complexity to achieve a decent efficiency, while turbines, with a much simpler design and a continuous cycle, were capable of an efficiency of over 40% at critical point, conditional on the usage of a re-heater and energy-saver, without which efficiency plateaus at 10-20. [54]

1.3.8 Conclusions

Turbines were used because of their lightness and ease of maintenance, but their high fuel consumption meant that, as fuel prices rose, Diesel engines became preferable. Some attempts are being made to employ them for high-speed trains, but lack of political will means there hasn’t been enough demand to make mass-producing turbine-powered trains viable, for now.
## Chapter 1: Context

### Table 1.1: Data on the powering and braking systems of gas turbine trains throughout history

<table>
<thead>
<tr>
<th>Name of HEP Engine</th>
<th>Type of Fuel</th>
<th>Power of Sup. Engine</th>
<th>Fuel Capacity (m³)</th>
<th>Top HEP speed</th>
<th>Carried Weight (t)</th>
<th>Tractive Effort (in kN)</th>
<th>Heating Brakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>JetTrain</td>
<td>Diesel</td>
<td>170</td>
<td>2.4</td>
<td>220</td>
<td>3.9</td>
<td>2.5</td>
<td>-</td>
</tr>
<tr>
<td>EMDF</td>
<td>Diesel</td>
<td>177</td>
<td>101</td>
<td>117.9</td>
<td>3.9</td>
<td>2.5</td>
<td>-</td>
</tr>
<tr>
<td>UACTurbo-Train</td>
<td>Diesel</td>
<td>274</td>
<td>4.9</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td>Amtrak Turboliner</td>
<td>Diesel</td>
<td>201</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SNCF Class T1000</td>
<td>Diesel</td>
<td>736</td>
<td>295</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SNCF Class T2000</td>
<td>Diesel</td>
<td>760</td>
<td>295</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TGV001</td>
<td>Diesel</td>
<td>318</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SBB-CFF-FFS Am4/6</td>
<td>Electric</td>
<td>110</td>
<td>110</td>
<td>162</td>
<td>1.03</td>
<td>70km/h</td>
<td>-</td>
</tr>
<tr>
<td>British Rail 18000</td>
<td>Diesel</td>
<td>145</td>
<td>1.9</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td>British Rail 18100</td>
<td>Electric</td>
<td>145</td>
<td>2.2</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td>APT-E</td>
<td>Diesel</td>
<td>224</td>
<td>5.1</td>
<td>2.3</td>
<td>85</td>
<td>70km/h</td>
<td>-</td>
</tr>
<tr>
<td>GE 5-Frame Gas Turbine</td>
<td>Diesel</td>
<td>105</td>
<td>3.4</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td>GE 752E</td>
<td>Diesel</td>
<td>145</td>
<td>2.2</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td>TGV001</td>
<td>Electric</td>
<td>110</td>
<td>110</td>
<td>162</td>
<td>1.03</td>
<td>70km/h</td>
<td>-</td>
</tr>
<tr>
<td>SBB-CFF-FFS Am4/6</td>
<td>Electric</td>
<td>110</td>
<td>110</td>
<td>162</td>
<td>1.03</td>
<td>70km/h</td>
<td>-</td>
</tr>
<tr>
<td>British Rail 18000</td>
<td>Diesel</td>
<td>145</td>
<td>1.9</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td>British Rail 18100</td>
<td>Electric</td>
<td>145</td>
<td>2.2</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td>APT-E</td>
<td>Diesel</td>
<td>224</td>
<td>5.1</td>
<td>2.3</td>
<td>85</td>
<td>70km/h</td>
<td>-</td>
</tr>
<tr>
<td>GE 5-Frame Gas Turbine</td>
<td>Diesel</td>
<td>105</td>
<td>3.4</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td>GE 752E</td>
<td>Diesel</td>
<td>145</td>
<td>2.2</td>
<td>0.2</td>
<td>24xND</td>
<td>750</td>
<td>-</td>
</tr>
</tbody>
</table>

### Notes
- Data on the powering and braking systems of gas turbine trains throughout history is presented in Table 1.1.
- The table includes information on the type of fuel, power output, and other relevant details for various gas turbine engines.

---

**Table 1.1: Data on the powering and braking systems of gas turbine trains throughout history**
Chapter 2

The Current Conjuncture

2.1 The suitability of electrification

The average cost of electrifying a rail line in France in mountainous terrain, such as in Picardie, may reach 2.4 million €/Km. The cost might be different in Spain depending on local laws and regulations.

The consultation and public inquiry are very heavy procedures; for instance, the Declaration of Public Utility may be subjected to legal action and appeal by public associations.

The Lleida-La Pobla line relies heavily on tourism, and traverses difficult terrain that will certainly make equipment constructions more expensive. On the ecological and aesthetic side, it does not seem wise to ‘disfigure’ the landscape with catenary overhead cables and electrical sub-stations, not to mention the transformers necessary to bring the 150-to-220V surrounding electric lines to the 25kV typical of a rail line.

Furthermore, the traffic density is very low, which does not help justifying an important investment for the line’s electrification.

In conclusion, to electrify this line would require a very serious economical study. Self-propelled Diesel vehicles seem an acceptable and sustainable status quo for the existing line and its exploitation mode (low traffic, relatively low speeds). Improvements should be sought within the rail vehicles themselves in order to attenuate the emissions, which can bother the local residents and the tourists.

A hybrid option might be considered if it were possible to harvest the needed energy from catenaries or electrical outlets on both sides of the touristic segments.

(Personal communication, Jamal Salam, Track Engineering Manager- Projects at ALSTOM TRANSPORT, September 6, 2014)
2.2 Tightening EU gas emission standards

European emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards.\[20][21][19]

Compliance is determined by running the engine at a standardised test cycle. Non-compliant vehicles cannot be sold in the EU, but new standards do not apply to vehicles already on the roads. New models introduced must meet current or planned standards, but minor lifecycle model revisions may continue to be offered with pre-compliant engines. In other words, the continued use of the available engines will not be a problem, but their renewal, barring electrification, would be.


The stages are typically referred to as Euro I, Euro II, Euro III, Euro IV, and Euro V for Heavy Duty Vehicle standards. European standards for non-road diesel engines harmonize with the US EPA standards, and comprise gradually stringent tiers known as Stage I-IV standards. The Stage I/II was part of the 1997 directive (Directive 97/68/EC). It was implemented in two stages with Stage I implemented in 1999 and Stage II implemented between 2001 and 2004. In 2004, the European Parliament adopted Stage III/IV standards. The Stage III standards were further divided into Stage III A and III B were phased in between 2006 and 2013. Stage IV standards will be enforced in 2014.

Stages I and II are omitted here because they did not have defined standards for locomotives or railcars. Passed on 21 April 2004, Directive 2004/26/EC amends Directive 97/68/EC to include ships, locomotives, and railcars. The directive outlines Stages III A, III B, and IV of emissions reduction standards. This new directive is aligned with the US proposal Tier IV of further stages of emission limit values. In the Directive, railcars and locomotives are defined as follows:

**Railcars**: Self-propelled, on-track vehicles that are designed to carry freight and/or passengers.

**Locomotives**: Self-propelled, on-track vehicles that are designed to propel cars that carry freight and/or passengers, but are not intended to carry goods or passengers themselves.

The different stages in the 2004/26/EC directive are as follows:

- Stage III A covers engines from 19 to 560 kW including constant speed engines, railcars, locomotives and inland waterway vessels.
- Stage III B covers engines from 37 to 560 kW including, railcars and locomotives.
- Stage IV covers engines between 56 and 560 kW.
- Stage III A and III B standards have been adopted for engines above 130 kW used for the propulsion of railroad locomotives (categories R, RL, RH) and railcars (RC). There are no upper limits concerning engine power.

Stage III/IV legislation applies only to new vehicles and equipment.
2.2. Tightening EU Gas Emission Standards

<table>
<thead>
<tr>
<th>Stage</th>
<th>Category</th>
<th>Net Power kW</th>
<th>Market Placement Date</th>
<th>CO</th>
<th>HC</th>
<th>HC+NOx g/kWh</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>III A</td>
<td>RC A</td>
<td>130 &lt; P</td>
<td>2006.01</td>
<td>3.5</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>RL A</td>
<td>130 ≤ P ≤ 560</td>
<td>2007.01</td>
<td>3.5</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>RH A</td>
<td>560 &lt; P</td>
<td></td>
<td>3.5</td>
<td>0.5</td>
<td>-</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>2000 &lt; P</td>
<td></td>
<td></td>
<td>3.5</td>
<td>0.4</td>
<td>-</td>
<td>7.4</td>
<td>0.2</td>
</tr>
<tr>
<td>III B</td>
<td>RC B</td>
<td>130 &lt; P</td>
<td>2012.01</td>
<td>3.5</td>
<td>0.19</td>
<td>-</td>
<td>2</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>R B</td>
<td>130 &lt; P</td>
<td>2012.01</td>
<td>3.5</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>0.025</td>
</tr>
<tr>
<td>IV</td>
<td>Q</td>
<td>130 ≤ P ≤ 560</td>
<td>2014.01</td>
<td>3.5</td>
<td>0.19</td>
<td>-</td>
<td>0.4</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>56 ≤ P &lt;130</td>
<td>2014.1</td>
<td>5</td>
<td>0.19</td>
<td>-</td>
<td>0.4</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Table 2.1: European Emission Standards for Rail Traction Engines

2.2.1 Other Provisions

There are other provisions that need to be followed, regarding:

**Reagents** - In after-treatment systems using reagents, such as urea in SCR systems for NOx control-monitoring, is required by the low reagent levels, reagent quality and dosing Directive 2010/26/EU.

**Fuels** - Reference fuel used for type approvals and to verify conformity of production at the Stage III A level should contain no more than 300 ppm sulphur. Some of the after-treatment technologies to be used for PM and NOx control to meet Stage III B and Stage IV limit values will require the use of ultra low sulphur fuel. Thus, the Stage III B and Stage IV reference fuel should contain no more than 10 ppm sulphur.

**Durability** - The engine useful life (emission durability period, EDP) is defined at Stage III/IV as 3000/5000 hours for engines at or below 37 kW (constant/non-constant speed, respectively) and 8000 hours for engines above 37 kW.

As of 2008, Ultra-low-sulphur Diesel, i.e. Diesel with a sulphur concentration of less than 10ppm, has been widely available throughout the EU, with Diesel with over 50ppm sulphur banned since 2005. Natural gas, on the other hand, is usually considered sour if there are more than 5.7 milligrammes of H2S per cubic meter of natural gas, which is equivalent to approximately 4 ppm by volume under standard temperature and pressure. In its crude state, natural gas can contain up to 90% H2S, being removed in refinery in the process known as sweetening.

2.2.2 Test Cycle

Engines for propulsion of railcars and locomotives are tested using a steady-state procedure (Non-Road Steady Cycle, NRSC). The testing procedure for railcars is identical with the C1 cycle of ISO8178. The procedure for locomotives is identical with the F cycle of ISO8187. Emission durability period (EDP) for Stage III/IV rail traction engines is 10,000 hours.

We have foregone the application of this standard cycle when making our simulation to avoid a cycle beating approach; the optimisation of emission performance to the test cycle, while emissions from typical driving conditions would be much higher than expected, undermining the standards and public health.\[18\]. See Figure 2.6-
2.3 CO2 Emissions to be Expected

According to the calculations of the Catalan Office for Climate Change[15], the 2.3 are the average emission rates to be expected of rail vehicles:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Emission Rate (g of CO2/passenger x km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-speed Renfe AVE</td>
<td>15.37</td>
</tr>
<tr>
<td>Renfe Cercanías (Suburban)</td>
<td>24.38</td>
</tr>
<tr>
<td>Renfe Media Distancia</td>
<td>19.47</td>
</tr>
<tr>
<td>FGC (Regional)</td>
<td>16.26</td>
</tr>
<tr>
<td>Tramway</td>
<td>26.40</td>
</tr>
<tr>
<td>Metro</td>
<td>25.45</td>
</tr>
</tbody>
</table>

Table 2.3: Emission rates of rail vehicles depending on type of service

The [15] also specifies 2.4

<table>
<thead>
<tr>
<th>ENERGETIC SOURCE</th>
<th>EMISSION RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (kWh)</td>
<td>181 g CO2/kWh 50</td>
</tr>
<tr>
<td>Natural Gas (m^3)</td>
<td>2.15 kg CO2/Nm^3</td>
</tr>
<tr>
<td>Butane Gas (kg)</td>
<td>2.96 kg CO2/kg gas butane</td>
</tr>
<tr>
<td>Propane Gas (kg)</td>
<td>2.94 kg CO2/kg de gas propane</td>
</tr>
<tr>
<td>Gasoil (litres)</td>
<td>2.79 kg CO2/l gasoil 51</td>
</tr>
<tr>
<td>Fuel (kg)</td>
<td>3.05 kg CO2/kg de fuel</td>
</tr>
<tr>
<td>Generic GLP (kg)</td>
<td>2.96 kg CO2/kg of generic GLP</td>
</tr>
</tbody>
</table>

Table 2.4: CO2 emission rates by type of fuel

No similar materials seem to exist for CO, NO, HC and particle emissions.

2.4 The suitability and cost-effectiveness of natural gas

2.4.1 Suitability regarding emissions

Natural gas is the hydrocarbon fuel hydrocarbon fuel that produces the least amounts of sulphur dioxide or other pollutants due to combustion listed below in parts per million (ppm)[16][17]:

- Carbon monoxide - 40 ppm
2.4. THE SUITABILITY AND COST-EFFECTIVENESS OF NATURAL GAS

- Sulfur dioxide - 1 ppm
- Nitrogen oxide - 92 ppm
- Particulates - 7 ppm

2.4.2 The Cost-Effectiveness of Gas Prices

Despite what one may assume from Spain’s role as a gateway for Algerian gas into Europe, as of 2012, the wholesale price of gas is very high, and above that of several other EU nations; Spain is thus not an exceptionally ideal environment to introduce Natural Gas as a fuel for vehicles. The ten nations in the world where Natural Gas is the cheapest turn out to be, from cheapest to most expensive: Turkmenistan, Algeria, Saudi Arabia, Oman, Qatar, Venezuela, the United Arab Emirates, Nigeria, Uzbekistan, and Bangladesh, being the first to cross the 2 USD/mmbtu (millions of British Thermal Units).

However, the primary factor that would make Natural Gas a viable alternative to Diesel fuel is not its absolute price, but the former’s price relative to the latter.

2.4.3 Future Projections of Gas Prices: Relative Economical Advantages

Following years of tight price linkage, spot prices for crude oil (North Sea Brent) and natural gas (Henry Hub) diverged around 2005. In 2012, the Brent spot price was about seven times the Henry Hub spot price on an energy equivalent basis. That differential is projected to narrow in the midterm, but a persistent gap is expected to continue, with crude oil prices more than three times higher than natural gas per millions of British Thermal Units (MMBtu) throughout the reference case projection period, going out to 2040.[22]

The large differential between crude oil and natural gas commodity prices translates directly into a significant disparity between projected LNG and diesel fuel prices, even after accounting for natural gas liquefaction costs that exceed refining costs. In the AEO2014 reference case, the long-run price difference between locomotive diesel fuel and LNG in rail applications increases from $1.48/gal of diesel equivalent in 2014 to $1.77 in 2040.[22]

Given the difference between LNG and diesel fuel prices in the reference case, railroads that switch locomotive fuels could accrue significant fuel cost savings. Locomotives are used intensively, consume large amounts of fuel, and are kept in service for relatively long periods of time. The net present value of future fuel savings across the reference case projection for an LNG locomotive compared to a diesel counterpart is well above the roughly $1 million higher cost of the LNG locomotive and tender.[22]
2.4.4 Challenges

- **Upfront Costs:** as covered in 2.4.3. Replacing the current stock of diesel locomotives with LNG locomotives and tender cars would represent a significant financial investment.

- **Operational:** a new infrastructure needs to be installed to cover the logistics of delivering the fuel to the locomotives. Natural gas would need to be delivered to fuel depots, either by truck in smaller quantities, as LNG, or perhaps by pipeline. Larger quantities of natural gas would require liquefaction before delivery to tender cars for use in locomotives.[22] Thanks to the thriving cogeneration industry, there is already, in the Lleida area, an industrial infrastructure capable of distributing the needed gas (see 2.6.1.1). In addition, operations could be further affected by fuel switching because of the cost of training staff at refueling depots and in maintenance shops, updating maintenance facilities to handle LNG locomotives and tenders, and managing more extensive logistics. Further, LNG locomotives and tender cars could require more maintenance than their diesel counterparts.[22]

- **Regulations:** as far as we could find, there are no regulatory provisions for vehicles employing natural gas as fuel. As of the writing of this document, we have been unable to ascertain whether there would be problems from the public administration.

- **Testing:** LNG locomotives currently are undergoing extensive testing and demonstration to determine their fuel consumption, emissions, operational performance, and range under real-world conditions. Developing an LNG train for the Lleida-La Pobla line might have
value as a proof of concept for the application of the technology to mid-range regional rail transportation.

### 2.4.5 Conclusion

EU regulations are becoming progressively more restrictive when it comes to emissions, and natural gas is cleaner than diesel fuel in this regard. Furthermore, diesel fuel has become much more expensive than natural gas, and is expected to remain so in the future. Natural gas thus appears to be the best option in the long term, as long as the infrastructure to distribute it is in place. (See also 2.5.1.2)

### 2.5 The suitability of gas turbines

Given equal fuel, gas turbines produce cleaner emissions than diesel turbines. Here we have a concrete example of a study that evaluated the emissions and consumption of a gas turbine powered locomotive as opposed to a Diesel-powered one.
2.5.1 The Pier Study

In 2002, a study[31] was made about retrofitting a pre-existing Diesel-electric locomotive with gas turbines in order to reduce NOx and particulate emissions. We have compared the characteristics of the train in question with the pre-existing vehicles and available brand-new material that could fit the needs of the line. We find that, while the Californian locomotive is at least twice as powerful as what we’re working with, the situations are comparable enough that we may extrapolate the results of the former to the latter. See Table 2.5 We’ve also attempted an approximation of each vehicle’s power using pre-existing Capstone gas-turbine-powered, natural-gas-fuelled cogeneration packages, the characteristics of which are listed in some detail in their respective technical sheets. See Section 2.6.2.1

2.5.1.1 Diesel vs. turbine engines

Conventional diesel electric locomotive throttle control is divided into 8 notches plus one idle position. The digital engine control unit can be programmed to deliver the same power response to throttle notch position as shown in the next graph. The graph also includes an optimum speed curve. The intersection of this curve with each power setting represents the turbine speed which will deliver optimum efficiency for the power demand.
2.5. THE SUITABILITY OF GAS TURBINES

The locomotive's original power train consists of a 12 cylinder, two stroke cycle, 3000 horse power diesel engine driving a 10 pole alternator at 800 rpm which in turn delivers 700 V DC of rectified power to drive four DC traction motors.

The percentage distribution table of the notch position used in the San Bernardino commuter line (see Figure 2.6) is representative of the type of cycle a rail transport vehicle must go through. It is apparent that the maximum notch position is only used only 26% of the time; those are unfavourable conditions for a gas turbine, which work at their best at maximum power, and perform poorly at lower intensities. This problem can be alleviated by using multiple turbines, so that, when running at low capacity, only a few of them are functioning, but those who are are running at maximum power. In this ([31]) case, two TF15 (AGT1500) turbines were employed, coupled in parallel.

A TF15 (AGT1500)'s dimensions are 1.689 x 9.91 x 0.808 m. It produces 1120 kW (1500 hp) for a weight of 1134 kg (2500 lbs.), 50.99kW/kg (0.6 hp/lb). A typical locomotive diesel produces about 0.024 kW/kg (0.07 hp/lb). Output speed is 21,700 rpm reduced to 3000 rpm by a planetary gear train, which allows usage of a standard alternator. (One could directly employ the original speed, which would allow for a much smaller and lighter alternator, at the price of employing non-standard equipment, with all the typical complications that would entail).

Figure 2.7 shows the specific fuel consumption as a function of power output for the TF15 as well as for a typical diesel engine and a non-recuperated, or conventional, gas turbine of similar
CHAPTER 2. THE CURRENT CONJUNCTURE

<table>
<thead>
<tr>
<th>Californian Passenger Train</th>
<th>Renfe Serie 592</th>
<th>Tourist Train *</th>
<th>CAF CIVITY</th>
<th>ALSTOM Coradia</th>
<th>Califormian Renfe Tourist TT CAF ALSTOM Passenge Serie 592 + &quot;Yeye&quot; *Garrafeta&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall weight</td>
<td>612 tn</td>
<td>130.4 tn</td>
<td>64 tn + carriages</td>
<td>170.250 tn + carr.</td>
<td>100 tn</td>
</tr>
<tr>
<td>Seated load</td>
<td>722 tn</td>
<td>153</td>
<td>140 km/h</td>
<td>120 km/h</td>
<td>160 km/h</td>
</tr>
<tr>
<td>Seats</td>
<td>200</td>
<td>200</td>
<td>60 km/h</td>
<td>60 km/h</td>
<td>160 km/h</td>
</tr>
<tr>
<td>Power:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel Engine</td>
<td>2238 kW</td>
<td>2x160 kW</td>
<td>520 kw</td>
<td>2.880kW</td>
<td>3x335 kW</td>
</tr>
<tr>
<td>Head End Power</td>
<td>582 kW</td>
<td>120 kVA</td>
<td>600 kVA</td>
<td>up to 600 kVA</td>
<td></td>
</tr>
<tr>
<td>Turbine replacements</td>
<td>2x1120 kW</td>
<td>4x200 kW</td>
<td>2x200+2x60*</td>
<td>4 x C800*</td>
<td>C1000</td>
</tr>
<tr>
<td>Equiv. Capstone Package</td>
<td>2xC1000</td>
<td>C800*</td>
<td>C600*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5: Comparison between Californian train, contemporary trains on the Lleida-La Pobla, and available brand-new trains. * are suggestions.

The light weight of the turbine drive lowers locomotive weight by as much as 34 tons, which lowers its specific fuel consumption an additional 18 g/kWh or 4%. Acceleration performance improves by 4% as well.

The TF 15 gas turbine has variable blading, which allows it to compensate for changes in ambient air temperature. Thus, the power output as rated at sea level and 10°C remains constant at ambient temperatures from -51°C to 31°C, rather than varying with changes in air density related to temperature. (See Fig. 2.8)

The article goes on to compare 3 possible solutions:

- Baseline: the locomotive’s original state, both the traction and the HEP engines are Diesel.
- Solution 1: turbine traction and HEP.
- Solution 2: turbine traction and Diesel HEP.

simulated on the train’s usual commute.

Figure 2.9 shows how using an all-turbine system causes the least emissions by a large margin in every category. It must also be said that it simplifies the logistics of refuelling the train, as it does not need it to rely on separate sources for gas and fuel.

In Figure 2.10 we see that going from full Diesel to full turbine increases the volume of diesel fuel consumed by about 20%.
2.5.1.2 Diesel fuel vs. LNG

LNG offers an alternative to diesel fuel oil for internal combustion engines. However, for the same range, LNG fuel tanks be 61% larger than diesel fuel tanks and, in addition, the tanks must be insulated to maintain the LNG at -164°C.

A diesel engine running on LNG has its power output typically fall to 55% of its rating with diesel fuel. On the other hand, gas turbines, because of the continuous nature of their combustion cycle, will run on natural gas without any loss of power. Experience has shown that service life of the turbine will be doubled as a result of the clean burning characteristics of the gas. See Figure 2.11: with both solutions running on natural gas, the NOx emissions are the same, but CO and HC emissions are much lower.

Figure 2.12 shows us that all of the emissions of the Solution 2-L locomotive are measurably lower than the Baseline-L resulting in a total emissions reduction of 33 kg/trip (46%) and the benefit for the Solution 2-L conversion is 7 kg/trip (10%).

2.5.1.3 Comparison with Capston systems

In Figure 2.8, we saw the effect that ambient temperature had on the efficiency of the TF 15 gas turbine. For comparison, Capston’s basic C200 200kW turbines show a similar drop in power at a slightly lower temperature (about 28°C), as shown in Figure 2.13.

In Figures 2.14, 2.15, and 2.16, we see the wisdom of load distribution, i.e. employing several small turbines instead of one that’s very large, and how it allows to circumvent the problem of lack of efficiency at low and medium power.


### 2.5.2 Conclusions

While gas turbines are slightly less energetically efficient than Diesel engines when using diesel fuel, they have consistently cleaner emissions regardless of fuel, and perform better than Diesel engines when using natural gas, which is even cleaner in terms of emissions.

### 2.6 Available Infrastructures

#### 2.6.1 Natural Gas Logistics

There need to be local companies able to safely and cheaply handle the supplying of gas to the train, as well as other related concerns. In the region of Lleida, there is one existing group:

#### 2.6.1.1 INDOX

Located in Tarrega, belongs to Ros Roca Group. They specialise in displacement and storage of Natural Gas in all its forms; of interest to us is their knowledge in regasification, gas stations, conversion of vehicles from Diesel to liquefied natural gas (LNG), and portable LNG tanks for great vehicles. They also manage biogas and generator groups.
2.6. AVAILABLE INFRASTRUCTURES

Figure 2.8: Power vs. inlet temperature of TF15

Figure 2.9: Emissions per trip for each solution

They convert Diesel trucks to LNG and have software that allows them to use the right pressure for each type of vehicle. Their website asserts that the upgrade is redeemable in three years, due to less fuel consumption, and less taxes on fuel and emissions, and also that it results in more silent, image-friendly trucks. However, upon contacting their technical staff, we have found out that their conversion package was discontinued; the maintenance costs turned out to be unexpectedly and unacceptably high.

They also build generator groups go from 60 to 1100 kW.

2.6.2 Cogeneration and Electrogenic Groups

2.6.2.1 Micropower Europe

[mblasco@micropowereurope.com]

Micropower Europe offers Capstone gas microturbines in Spain and Portugal, as well as micro-generation applications.

The gas turbines gyrate at an angular velocity between 15000 and 20000 RPM. Gas turbines usually employ several stages of compression and turbine energy extraction, and a gear train on exit to reduce axis speed.

Microturbines simplify this to one moving part of compression and turbine and generator-coupled axis. Air cushions? no lubrication air refrigeration remote control integrated network
protection.] allow them to reach 96000 rpm, and the generation frequency is adapted using power electronics. They use regenerative Brayton cycles, preheating the compressed entry air, reaching 33% performance for a 200kWe turbine.

In either case, the high rotational velocity may be the opportunity to install a very small, compact alternator, which would allow for great weight reduction and easier refrigeration.

The emission gas, at 300°C, can be reused, either for its heat as such.

According to the manufacturer, the microturbines does not lose efficiency when using less powerful forms of gas such as biogas.

There’s also capacity to accept $H_2S$ as long as the escape gas is not reused. [How so? Isn’t this a big problem?]

The microturbine is stated to be capable of maintaining 85% of its optimal efficiency at half load.

A useful idea proposed by the manufacturer when planning for installations that have fluctuating demand is that of modularity: the usage of several, smaller, independent generation groups, rather than a single large engine. The advantages are as follows:

- Each individual engine spends less time turning, thus slowing the accumulation of fatigue, and lengthening their life cycle. [Should I add an explanatory diagram?]
2.6. AVAILABLE INFRASTRUCTURES

At any time, most engines will be functioning at high capacity, making the most of the turbines’ efficiency. It is better to have two turbines small turbines, working part time rather than one big turbine, working full time, but at half power. [!A simple series of equations to hammer the point home?]

At very small output rates, a large turbine engine may not be able to run at all.

Large turbine engines are slow to start up and to adjust in speed, due to the large angular momentums involved: smaller engines offer much quicker responses to changing energy needs.

The common characteristics of all the packages they offer that run on natural gas are detailed in Table 2.6, and the specific characteristics of each package in Table 2.7:

2.6.2.2 Talleres GEA

d GEA are a family company of several brothers who build power generator groups customised to the client’s needs. They are based in Balaguer.
2.6.3 Rolling Stock Manufacturers

There are several local builders capable of developing the rolling materials or the infrastructures. They would be of particular interest to the Generalitat if they were to decide to buy new vehicles outright instead of retrofitting old ones:

2.6.3.1 CAF

CAF are a railway technology manufacturers based in Guipuzcoa, in the Basque Country.

CAF studies viability, civil engineering, electrification, signalling, maintenance and system operation, via turn-key arrangement or via concession.

Of particular interest to us is that they build regional trains, such as the Civity. Designed for Standard Gauge, their trains are available with Electric, Diesel (mechanical, hydraulic or electric transmission), or hybrid. The trains are very modular and adaptable. Duo models have a second floor, XL have larger waggons (that do not share bogies). Nominal traction power for a typical Cicity model is 2.88MW; maximum axle power is 4MW.

Their CAF Power & Automation division manage the electronic control systems.
### 2.6. AVAILABLE INFRASTRUCTURES

#### Figure 2.16: Efficiency vs. power of C1000

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Heat Rate LHV</td>
<td>10.9 MJ/kWh</td>
</tr>
<tr>
<td>Voltage</td>
<td>400-480AC</td>
</tr>
<tr>
<td>Electrical Service</td>
<td>3-Phase 4-Wire</td>
</tr>
<tr>
<td>Frequency</td>
<td>10-60 Hz</td>
</tr>
<tr>
<td>Natural Gas HHV</td>
<td>30.7 47.5 MJ/m3</td>
</tr>
<tr>
<td>Inlet Pressure</td>
<td>517 552 kPa</td>
</tr>
<tr>
<td>Acoustic Emissions</td>
<td></td>
</tr>
<tr>
<td>at Full Load Power</td>
<td>65 dBA</td>
</tr>
<tr>
<td>Nominal at 10 m</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.6: Common characteristics of all Capston electrogenic groups

#### 2.6.3.2 Bombardier

Bombardier have had some experience in constructing the JetTrain, and in building regional and commuter trains for several countries, and have factories in the Basque country as well.

#### 2.6.3.3 ABB

ABB, formerly Bon Bovery, have vast engineering capabilities in practically every aspect of the development and construction of this railway project that we might need, from the construction of the whole train to the specific tuning of any particular element, to the establishment of infrastructures surrounding it, and they have several factories and centres throughout Spain.

#### 2.6.3.4 Siemens

It absorbed Westinghouse, one company with previous experience with turbine trains, and they otherwise have strong capabilities and experience both in the construction of rail vehicles and in that of cogeneration systems.

#### 2.6.3.5 Alstom

Alstom have several locations in Catalonia and are the Generalitat’s go-to provider of railway solutions. They also have a lot of expertise in electricity generation systems.
CHAPTER 2. THE CURRENT CONJUNCTURE

<table>
<thead>
<tr>
<th></th>
<th>C65</th>
<th>C200</th>
<th>C600</th>
<th>C800</th>
<th>C1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Power Output</td>
<td>65kW</td>
<td>200kW</td>
<td>600kW</td>
<td>800kW</td>
<td>1000 kW</td>
</tr>
<tr>
<td>Maximum Output Current</td>
<td>100A</td>
<td>310A RMS</td>
<td>930A RMS</td>
<td>1,240A</td>
<td>1,550A RMS</td>
</tr>
<tr>
<td>Electrical Efficiency LHV</td>
<td>29%</td>
<td>33%</td>
<td>33%</td>
<td>33%</td>
<td>33%</td>
</tr>
<tr>
<td>Fuel Flow HHV</td>
<td>888 MJ/hr</td>
<td>2,400 MJ/hr</td>
<td>7,200 MJ/hr</td>
<td>9,600 MJ/hr</td>
<td>12,000 MJ/hr</td>
</tr>
<tr>
<td>NOx Emissions</td>
<td>&lt;9 ppmvd</td>
<td>&lt;9 ppmvd</td>
<td>&lt;4 ppmvd</td>
<td>&lt;4 ppmvd</td>
<td>&lt;4 ppmvd</td>
</tr>
<tr>
<td>@ 15% O2 (mg/m³)</td>
<td>19 mg/m³</td>
<td>18 mg/m³</td>
<td>8 mg/m³</td>
<td>8 mg/m³</td>
<td>8 mg/m³</td>
</tr>
<tr>
<td>NOx / Electrical Output</td>
<td>0.14 g/bhp-hr</td>
<td>0.14 g/bhp-hr</td>
<td>0.05 g/bhp-hr</td>
<td>0.05 g/bhp-hr</td>
<td>0.05 g/bhp-hr</td>
</tr>
<tr>
<td>Exhaust Gas Flow</td>
<td>0.49 kg/s</td>
<td>1.3 kg/s</td>
<td>4.0 kg/s</td>
<td>5.3 kg/s</td>
<td>6.7 kg/s</td>
</tr>
<tr>
<td>Exhaust Gas Temperature</td>
<td>309°C</td>
<td>280°C</td>
<td>280°C</td>
<td>280°C</td>
<td>280°C</td>
</tr>
<tr>
<td>Exhaust Energy</td>
<td>112kW</td>
<td>1,420 MJ/hr</td>
<td>4,260 MJ/hr</td>
<td>5,680 MJ/hr</td>
<td>7,100 MJ/hr</td>
</tr>
<tr>
<td>Width x Depth x Height</td>
<td>0.76 x 2.0 x 1.9 m</td>
<td>1.7 x 3.8 x 2.5 m</td>
<td>2.4 x 9.1 x 2.9 m</td>
<td>2.4 x 9.1 x 2.9 m</td>
<td>2.4 x 9.1 x 2.9 m</td>
</tr>
<tr>
<td>Weight</td>
<td>1121 kg</td>
<td>3413 kg</td>
<td>15014 kg</td>
<td>15558 kg</td>
<td>20956 kg</td>
</tr>
</tbody>
</table>

Table 2.7: Specific characteristics of all Capston electrogenic groups

2.6.3.6 General Electric

Several companies with previous experience in developing gas turbine trains, such as Metropolitan-Vickers, English-Electric, British Leyland, were absorbed by General Electric, whose current, pan-European rail services are specialized in the field of freight transportation.

2.6.3.7 On Diesel engines and emission regulations

A cursory study of these firms’ brochures indicates that the emissions of the new Diesel-electric trains they’re manufacturing are compliant with current EU exhaust emission norms. This is nice.

2.7 Possible further improvements

2.7.1 Improving Energy Efficiency

The switch to a gas turbine and a natural gas fuel, with the provisions previously discussed, would save energy and reduce emissions in the long run, but it might be possible to save even more energy through further technical measures:

- It may be possible to take advantage of air intake/draft tube of to cool the alternator and provide the turbine with hotter air on entry.
- The high-frequency noise of turbines has been a great source of complaints in the past, but, with modern soundproofing technology, it is easy to muffle, to the point that it is no more noisy than an electric train of equivalent power. (See section 1.3.4.4)
- It might be possible to employ the cold energy that the LNG absorbs upon vaporizing to cool the alternator through cryogenics (Sec. 2.7.1.2)
- That the train uses electric propulsion affords us the opportunity to employ the electric motors as brakes, thus reducing the maintenance costs of the brakes. This braking energy could be further exploited in one of two ways:
2.7. POSSIBLE FURTHER IMPROVEMENTS

**dynamic braking:** using resistances to dissipate the braking energy as heat, which can be used as a heat source in the train, or dissipated outside. From the example of the AM 4/6, we know it might be possible to employ the dynamic braking to power the compressor without spending oil during long descents.

**regenerative braking:** using the engines as alternators, convert the braking energy into electricity. It’s more technically challenging, especially given that the rail is not electrified, and the electric energy would have to be stored onboard, which might not be cost or weight-effective, depending on the technology employed, although KERS (kinetic energy recovery systems) might be worth looking into. Flywheels in particular are an energy storage system that have the advantage of being able to store much more energy per weight than the standard alternatives of batteries, supercapacitors, or hydraulic storage systems.\[55]\[56]\[57]

- It could be better to employ several small generation groups than a single large one.
- All the water-intensive usages suggested in 2.7.2 require considering how much water the train needs to carry with it, and where it may re-supply.
- Lukaszewicz (2009)\[38] concludes that the most important factors in reducing CO2 emissions per passenger per kilometre were:
  - the effect of wind resistance, which is proportional to the speed squared: even small improvements in aerodynamics, and reductions in speed, can have dramatic effects on the energy spent.
  - the driving style, especially the dosage of coasting and acceleration, which can be automated and optimized
  - the amount of passengers on the train at any time vz. its capacity, i.e. the train’s passenger load rate: proper management of train capacity can improve these numbers drastically, and modularity is an essential capacity to keep the trains exactly as large as they need to be at any time. Proper design of the trains themselves, and an optimized configuration of the seats, can significantly increase the number of passengers a unit of a given length can carry.

2.7.1.1 Exploitation of the Exhaust Heat

There are several ways to make use of the relatively high temperature of exhaust gases.

As the exhaust emissions exit the turbine at a rather high temperature, there is an opportunity to recover this energy. Some potential uses are:

- a source of heat for a Rankine cycle or Kalina cycle.
- a source of central heating for the train, by way of a boiler.
- conversely, it could be used for air conditioning, as a hot source for a heat pump, more specifically an absorption refrigerator.
- used directly for cooking.
- harmoniously combine some or all of the above via trigeneration technologies.
Micropower offers us one example of such a Rankine cycle engine (See Table 2.8 and Figures 2.17 and 2.18).

As we know (see Table 2.7), a C1000 emits, at nominal full power and ISO conditions, 6.7 kg/s of 280°C gas emissions; that’s 24120 kg of gas per hour. According to Table 2.8, with entry gases at 260°C for a power output of 125kW, we’d need a flow of 34091 kg/hr, while at 315.6°C we’d need a smaller flow of 22500 kg/h. It seems that, by adding this 3tonne module to the system, we may be able to extract a little less than 125kW of energy from the otherwise-wasted exhaust gases. Depending on how the additional weight may affect the train’s fuel consumption, the addition of such a system might prove to be worthwhile.

2.7.1.2 Superconduction

Superconductivity is a phenomenon of exactly zero electrical resistance and expulsion of magnetic fields occurring in certain materials when cooled below a characteristic critical temperature. In 1986, it was discovered that some cuprate-perovskite ceramic materials have a critical temperature above 90 K (-183 °C) [34]. Other high-temperature superconductors have been discovered.
### 2.7. POSSIBLE FURTHER IMPROVEMENTS

since, and critical temperatures range from 20K for $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ to 134K for $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_8$. Natural gas (which is often mostly made of methane) liquefies at close to atmospheric pressure by cooling it to approximately 111K (-162 °C). Methane has a vaporisation enthalpy of 512kJ/kg. A Micropower C1000 system consumes 12,000 MJ/hr (higher heating value). Natural gas has different higher heating value values depending on country of origin; Algerian gas, the sort most likely to be found in Catalonia, has one of 42.00 MJ/m³. That’s 285.71 m³/h. The density of gas methane is 0.656 g/L (or kg/m³) at 25 °C, 1 atm. That’s 187kg/h, so an intensity of vaporisation enthalpy of 95960kJ/h; 26.65 kW.

Let’s assume the alternators of the C1000 have a 0.92 efficiency rate. They are rated to generate 1000kW; that would mean 86.95kW of losses: about 3.2 times as much as the evaporation of the natural gas can absorb. We would need a 97.40 efficiency at least for the evaporation enthalpy of the gas to completely cover the heat losses of the alternator. However, such an efficiency is not unheard-of, and, once we get close to superconduction temperatures, resistances would drop dramatically, resulting in a virtuous cycle that would ensure that the generators’ losses remain minimal if not null throughout the trip.

Superconductor materials have become more affordable recently: in 2002, American Superconductor sold wire for $200 per kiloamp per metre, and expected to reduce the cost to about $50 per kiloamp per metre upon opening a new production plant the following year.[36] As of the time of this writing, it is safe to assume that prices have fallen even lower, though not so low as the $25 per kiloamp per metre of copper. However, they have become affordable enough that this particular application may turn out to be worthwhile; at least, further calculations in this direction seem justified.

### 2.7.2 Environmental and Social Impact

Maximizing the popularity of the ride and its usage, both for its own sake as well as for the sake of increasing tourism in the region and providing the locals themselves with opportunities for welfare and entertainment, is essential to justifying its continued existence.

#### 2.7.2.1 The train as a power source, and as a pleasure resort

- When the train is stopped at the terminus station, it might be possible to exploit it as part of an electrical micronetwork.
- If the propulsion motors are distributed throughout the train, the generation group should be at the back of the train so that the gasses can’t hurt or trouble the passengers, especially while inside tunnels, of which there are a few particularly long ones (See 1.1.1.
- It might be possible to exploit the train’s portable, powerful generator in several capacities, from rescue missions to light and music spectacles.
- Specially designed entertainment modules could increase the train’s touristic attractiveness, turning it into an authentic entertainment ride in its own right.
  - a hot shower/bath coach would make for a portable hot springs.
  - open-topped coaches would provide the passengers with an enhanced experience of the spectacular vistas visible in the Lleida-La Pobla rail line.
with the appropriate technical equipment and security provisions, and in the right spots, the train could be used as a platform for swimming in the lakes, trekking through the forests, climbing the mountains, and otherwise making full use of the spectacular natural environments it traverses.

- it is possible to line the many tunnels with posters and lights to produce visual spectacles such as time-lapse animation.

- The calcotada: a catalan tradition is to grill spring onions in the open air. If the train has a biocombustible module, it might be possible to repurpose the embers for this kind of traditional gastronomic entertainment, draw crowds to the train station, and involve the local populace in the railway, giving them a better view of their tax euros at work.

2.7.2.2 The Train as a Museum and a wonder

Compared to retrofitting the propulsion systems, it would not be very expensive to outfit the train with the technology necessary to turn the ride into a full-on museum and guided tour. The region has a lot of fuel for curiosity and entertainment, and many tales to be told. The history of the region’s villages, the industries that made them flourish, and those that sunk them. Said history would be incomplete without that of the technology of the power plants, mines, railways and factories involved. The natural sights, the wildlife, the mounts and cliffs. The villages with their churches and monuments. From static billboards, to interactive touchscreens, to ‘audio tour’ guides that would describe the sights, exhibits and wonders to the passengers at the press of a button. It might not even be necessary to make specific accommodations when a well-designed mobile phone app could do an excellent job of it on its own - this could be as simple as reading audio files, or as complex as an augmented-reality system labeling the elements of the landscape as they pass by.

The train itself, and the technology involved in constructing it, may well be a more than adequate subject matter, especially if any new features, such as a gas turbine propulsion, are emphasized as ‘novel’, ‘innovative’ and ‘futuristic’.
### ISO Electric Performance

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net power</td>
<td>125 kW</td>
</tr>
<tr>
<td>Net electrical efficiency</td>
<td>14 %</td>
</tr>
</tbody>
</table>

### ISO Combustible consumption

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumed power at 100% load</td>
<td>880 kW PCI approx.</td>
</tr>
<tr>
<td>Combustibles</td>
<td>Any heat source at over</td>
</tr>
<tr>
<td></td>
<td>130°C (water, vapor, hot gas)</td>
</tr>
</tbody>
</table>

### Dimensions

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>3.175 kg</td>
</tr>
</tbody>
</table>

### Pressurized Hot Water to Power

### Waste Heat Conditions

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Temperature</td>
<td>143.3°C</td>
</tr>
<tr>
<td>Outlet Temperature</td>
<td>126.7°C</td>
</tr>
<tr>
<td>Input Energy</td>
<td>980kW</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>54343 kg/hr</td>
</tr>
</tbody>
</table>

### Condensing @ ISO Ambient: 15°C 60% RH

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensing Temperature</td>
<td>21°C</td>
</tr>
<tr>
<td>Condensing Load</td>
<td>821 kW</td>
</tr>
</tbody>
</table>

### Saturated Steam to Power

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>124°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>220.6 kPa</td>
</tr>
<tr>
<td>Flow</td>
<td>1678 kg/hr</td>
</tr>
</tbody>
</table>

### Hot Gases to Power

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Gas Inlet Temperature</td>
<td>204°C, 68182 kg/hr</td>
</tr>
<tr>
<td></td>
<td>260°C, 34091 kg/hr</td>
</tr>
<tr>
<td>Hot Gas Flow Rate</td>
<td>315.6°C, 22500 kg/hr</td>
</tr>
<tr>
<td></td>
<td>371.1°C, 16773 kg/hr</td>
</tr>
<tr>
<td></td>
<td>426.7°C, 13295 kg/hr</td>
</tr>
<tr>
<td></td>
<td>482.2°C, 11023 kg/hr</td>
</tr>
</tbody>
</table>

### Gas temperature needed for power output of 125kWe

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>315.6°C, 22500 kg/hr</td>
</tr>
<tr>
<td></td>
<td>371.1°C, 16773 kg/hr</td>
</tr>
<tr>
<td></td>
<td>426.7°C, 13295 kg/hr</td>
</tr>
<tr>
<td></td>
<td>482.2°C, 11023 kg/hr</td>
</tr>
</tbody>
</table>

Table 2.8: Technical sheet of the Capstone Clean Cycle 125kW Waste Heat to Electricity Generator
Chapter 3

Decisions

Our model of the train is incomplete, but has allowed us to highlight further paths of investigation:

- We were unable to construct a model of the thermal cycles involved in the functioning of the thermal engines, and in the recuperation of exhaust gas energy thereof. It should be noted that such cycles are kept under strict privacy restrictions by the builders.

- We were also unable to model the electric propulsion systems or the electrical power transmission gear.

- We do not know for certain how having a kinetic energy recovery system would interact with the power gear in terms of

- We did not consider the possibilities offered by fuel cell technology, mechanics and control, nor how it would impact total energy consumption.

- We are unable to provide an estimation for the cost of the installation of a new train, and its operation and maintenance costs in the long term, for each of the multiple combinations of technological options available.

However, within the limited scope of this project, we have managed to establish a certain number of conclusions with some confidence:

- **Electrification is not an option on the Lleida-La Pobla line**, due to high initial investment costs and aesthetic reasons.

- In the long term, natural gas is going to remain the cheaper alternative in relation to diesel fuel (see 2.4.2). Natural gas also causes less emissions, which is a strong point in the face of progressively more stringent regulations (see 2.2), and also helps reduce maintenance costs in the motor (see 2.5.1). **Natural gas seems therefore to be the fuel of choice.**

- Although normally they are more energy-efficient, Diesel engines have a low power-to-weight ratio relative to gas turbines, and this is exacerbated when the fuel used is natural gas[31]. Gas turbines also are less maintenance-intensive and, it is possible to further exploit their high-temperature exhaust gasses for other uses. **Gas turbines seem therefore to be the thermal engines of choice.**
There are, in the Lleida region, the local natural gas distributors, makers of gas turbine energy systems, and makers of electrical engines, necessary to effect the needed conversions to the rolling material and to the logistical chain, as well as provide the logistical and technical support a new, natural-gas-fuelled, gas-turbine-powered system would require. *The industrial infrastructure, the skills and technologies, are available.* (See 2.6).

There are multiple paths towards further increasing the energetic efficiency of the train. However, the key element to making the train cost-effective is to increase its passenger load ratio, to make it more attractive, as well as to maximize its social and ecological impact. (See 2.7.2)

---

**Glossary**

- **absorption refrigerator** refrigerator that uses a heat source (e.g., solar energy, a fossil-fueled flame, waste heat from factories, or district heating systems) as the source of the energy needed to drive the cooling process. 43, 71

- **active tilting technology** The Active Curve Tilting technology is designed to counter the effects of centrifugal force when turning into corners. It angles the car into curves providing an additional few degrees of roll toward the inside of the turn in order to lessen the lateral acceleration experienced by the passengers of the car. 20, 71

- **Amtrak** The National Railroad Passenger Corporation, doing business as Amtrak, is a publicly funded railroad service operated and managed as a for-profit corporation[1] which began operations on May 1, 1971, to provide intercity passenger train service in the United States. 21, 71

- **ANF Industrie** Ateliers de Construction du Nord de la France was a French locomotive manufacturer, based at Crespin in the Arrondissement of Valenciennes, northern France. Later known as ANF Industrie or ANF the company was acquired by Bombardier Transportation in 1989 and is now part of Bombardier Transport France S.A.S. 20, 71

- **ARMF** Associació per a la Reconstrucció i Posta en Servei de Material Ferroviari Històric. 17, 71

- **axle load** the total weight felt by the roadway for all wheels connected to a given axle, i.e. the fraction of total vehicle weight resting on a given axle. Exceeding the maximum rated axle load will cause damage to the roadway or rail tracks. 71

- **biogas** Biogas typically refers to a mixture of gases produced by the breakdown of organic matter in the absence of oxygen. Biogas can be produced from regionally available raw materials such as recycled waste. It is a renewable energy source and in many cases exerts a very small carbon footprint. 38, 71

- **Biomass** Biomass is biological material derived from living, or recently living organisms. It most often refers to plants or plant-based materials which are specifically called lignocellulosic biomass. A lot of the abandoned narrow-rail railways in Catalonia’s rural areas were designed to help deliver this kind of fuel to urban and industrial centres. 71
bogie the chassis or framework that transmits the weights of the rail cars to the carrying wheels. It may be shared between cars, or each car may have its own pair of bogies. In a rail context, they usually carry their own suspensions within them, and are mounted on a swivel..  19, 21, 71

Brake Van  .  71

Brayton cycle a thermodynamic cycle that describes the workings of a constant pressure heat engine. Gas turbine engines and airbreathing jet engines use the Brayton Cycle..  37, 71

Brown, Boveri & Cie (BBC) was a Swiss group of electrical engineering companies, producing DC Motors, AC motors, generators, steam turbines, gas turbines, transformers and the electrical equipment of locomotives. It was founded in Baden, Switzerland, in 1891 by Charles Eugene Lancelot Brown and Walter Boveri who worked at the Maschinenfabrik Oerlikon. In 1970 BBC took over the Maschinenfabrik Oerlikon. In 1988 it merged with ASEA to form ABB..  19, 71

buffet car where food can be purchased by the passengers, often has cooking equipment.  71

cadastral registration a comprehensive register of the real estate or real property’s metes-and-bounds of a country..  71

cogeneration cogeneration or combined heat and power (CHP) is the use of a heat engine or power station to simultaneously generate electricity and useful heat.  .  29, 71

condenser A condensing steam locomotive differs from the usual closed cycle condensing steam engine, in that the function of the condenser is primarily either to recover water, or to avoid excessive emissions to the atmosphere, rather than maintaining a vacuum to improve both efficiency and power. It takes the form of a series of pipes, valves and other ancillary equipment usually attached to an otherwise conventional steam locomotive. The apparatus takes the exhaust steam that would normally be lost up the chimney and routes it through a heat exchanger, into the normal water tanks. Installations vary depending on the purpose, design and the type of locomotive to which it is fitted..  71

consist or formation The group of rail vehicles making up a train, or more commonly a group of locomotives connected together for Multiple-Unit (MU) operation..  71

Continuous Brake chain, air, vacuum, (hose: simple or automatic, failsafe, Westinghouse).  71

criogenics The branches of physics and engineering that involve the study of very low temperatures, how to produce them, and how materials behave at those temperatures..  42, 71

dynamic braking Dynamic braking is the use of the electric traction motors of a railroad vehicle as generators when slowing down. It is termed rheostatic if the generated electrical power is dissipated as heat in brake grid resistors, and regenerative if the power is returned to the supply line..  19, 53, 71

EEC European Economic Community.  17, 71

Feedwater supply tank how much water does the train need?.  71

Felipe Gonzalez Felipe González Márquez is a Spanish social-democratic politician. He was the General Secretary of the Spanish Socialist Workers’ Party (PSOE) from 1974 to 1997. To date, he remains the longest-serving Prime Minister of Spain, after having served four successive mandates from 1982 to 1996..  18, 71
FGC  Ferrocarrils de la Generalitat de Catalunya. 18, 71

**head-end power**  is the electrical power distribution system on a passenger train, a.k.a. 'electric train supply' or 'Hotel Electric Power'. The power source, usually a locomotive at the front or 'head' of a train (or a generator car), provides the electricity used for lighting, electrical and other 'hotel' needs. 21, 22, 71

**heat pump**  A heat pump is a device that provides heat energy from a source of heat or "heat sink" to a destination. Heat pumps are designed to move thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses some amount of external power to accomplish the work of transferring energy from the heat source to the heat sink. 43, 71

**Henry Hub**  A natural gas pipeline located in Erath, Louisiana that serves as the official delivery location for futures contracts on the NYMEX. The Henry Hub is owned by Sabine Pipe Line LLC and has access to many of the major gas markets in the United States. As of June 2007, the hub connects to four intrastate and nine interstate pipelines, including the Transcontinental, Acadian and Sabine pipeline. [23]. 29, 71

**HEP**  see head-end power. 71

**higher heating value**  The quantity known as higher heating value (HHV) (or gross energy or upper heating value or gross calorific value (GCV) or higher calorific value (HCV)) is determined by bringing all the products of combustion back to the original pre-combustion temperature, and in particular condensing any vapour produced. Such measurements often use a standard temperature of 25°C. This is the same as the thermodynamic heat of combustion since the enthalpy change for the reaction assumes a common temperature of the compounds before and after combustion, in which case the water produced by combustion is liquid. 44, 71

**Kalina cycle**  The Kalina cycle is, like the Rankine cycle, a thermodynamic process for converting thermal energy into usable mechanical power, the difference being that it uses a solution of 2 fluids with different boiling points for its working fluid. Since the solution boils over a range of temperatures as in distillation, more of the heat can be extracted from the source than with a pure working fluid. The same applies on the exhaust (condensing) end. This provides efficiency comparable to a combined cycle, with less complexity. 43, 71

**LNG**  liquefied natural gas. 34, 36, 71

**locomotive**  A self-propelled unit of equipment, designed solely for moving other equipment. 71

**locomotive consist**  A combination of self-propelled units of equipment under a single control, and designed solely for moving other equipment. 71

**Lower heating value**  The quantity known as lower heating value (LHV) (net calorific value (NCV) or lower calorific value (LCV)) is determined by subtracting the heat of vaporization of the water vapor from the higher heating value. This treats any H2O formed as a vapor. The energy required to vaporize the water therefore is not released as heat. LHV calculations assume that the water component of a combustion process is in vapor state at the end of combustion, as opposed to the higher heating value (HHV) (a.k.a. gross calorific value or gross CV) which assumes that all of the water in a combustion process is in a liquid state after a combustion process. 71
millions of British Thermal Units The British thermal unit (BTU or Btu) is a traditional unit of energy equal to about 1055 joules. It is the amount of energy needed to cool or heat one pound of water by one degree Fahrenheit. In science, the joule, the SI unit of energy, has largely replaced the BTU. In natural gas, by convention 1 MMBtu (1 million BTU) = 1.054615 Giga Joules.. 29, 71

MMBtu millions of British Thermal Units. 29, 71

North Sea Brent Crude A type of oil that is sourced from the North Sea. This type of oil is used as a benchmark to price European, African and Middle Eastern oil that is exported to the West.[23]. 29, 71

Passenger Wagons turn the train into a museum, a posted tour.. 71

Payback Period The length of time required to recover the cost of an investment. The payback period of a given investment or project is an important determinant of whether to undertake the position or project, as longer payback periods are typically not desirable for investment positions.[23]. 71

power-car a vehicle that propels, and commonly also controls, a passenger train or tram, often as the lead vehicle, or a vehicle equipped with machinery for supplying heat or electrical power to other parts of a train. 71

PTO A power take-off or power takeoff (PTO) is any of several methods for taking power from a power source, such as a running engine, and transmitting it to an application such as an attached implement or separate machines.. 71

railbed the groundwork onto which a railway track is laid. 22, 71

Rankine cycle The thermal process by which steam-operated heat engines commonly found in thermal power generation plants generate usable mechanical power from thermal energy.. 43, 71

regasification a process of converting liquefied natural gas (LNG) at -162 °C temperature back to natural gas at atmospheric temperature. Many valuable industrial byproducts can be produced using cold energy of LNG, such as for extracting liquid oxygen and nitrogen gas from air, which is useful in, for instance, integrated steel plants and/or urea plants.. 36, 71

regenerative a cycle in a steam engine using heat that would ordinarily be lost: such as: a multiple-expansion steam-engine cycle in which the receivers are used as successive feed-water heaters; a steam-turbine cycle in which the condensate or feed water is heated to a temperature that is much higher than that corresponding to saturation at the exhaust pressure by means of steam that has been bled from the turbine at points intermediate between the throttle and exhaust. 37, 71

regenerative braking see dynamic braking. 71

Renfe Red nacional de ferrocarriles españoles. 17, 18, 71

Rohr Inc. An aerospace manufacturing company based in Chula Vista, California, south of San Diego. Made several forays into mass transit transportation in the 1970’s. Fully bought by the Goodrich Corporation, which in turn was bought by United Technologies Corporation.. 21, 71
steam generator A steam generator is a type of boiler used to produce steam for climate control and potable water heating in railroad passenger cars. The output of a railroad steam generator is low pressure, saturated steam that is passed through a system of pipes and conduits throughout the length of the train. 71

Swiss Federal Rail Lines is the national railway company of Switzerland. It is usually referred to by the initials of its German, French and Italian names, either concatenated as SBB CFF FFS, or used separately. 19, 71

track gauge the spacing of the rails on a railway track, measured between the inner faces of the load-bearing rails. Iberian gauge is the name given to the track gauge most extensively used by the railways of Spain and Portugal: 1,668 mm (5 ft 5 2132 in). This is the second widest gauge in regular use anywhere in the world. 18, 71

trigeneration Trigeneration or combined cooling, heat and power (CCHP) refers to the simultaneous generation of electricity and useful heating and cooling from the combustion of a fuel or a solar heat collector. 43, 71

Western Region of British Railways formerly The Great Western Railway (GWR), a British railway company that linked London with the south-west and west of England and most of Wales. Founded in 1833, nationalized in 1947 into the Western Region of British Railways. 71
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Appendices
Appendix A

Calculations and Modeling

In this part, we will establish the bases for a mathematical models that would be employed to perform the numerical calculations predicting the behaviour and performance of the train along the Lleida-La Pobla line, depending on certain behaviour protocols. These models would be implemented using the mathematical tools Matlab and Simulink.

We have tried to build a Matlab and Simulink program that would represent, instant by instant, the behaviour of the train on the rail, and the resulting energy demands, based on Łukaszewicz, 2001[37] (pages 55 to 77) and Steimel, 2008[43] (chapter 2). However, we were unable to complete a satisfactory model before the deadline: having practically no training as a programmer, we found ourselves struggling with the implementation of the established concepts.

Just as importantly, the information available only allowed us to calculate instantaneous power demands, but we were unable to find models for the behaviour of the upper echelons of the energy chain, notably the electric motors and alternators and the gas turbines and their thermodynamic systems. Given that their behaviour is highly dependent on transitory states, we believe that any calculation that does not take this into account will fail to make accurate estimates of the train’s behaviour.

Furthermore, Łukaszewicz’s work is highly focused on Swedish rails and vehicles, and their specific characteristics and regulations, and extrapolating his results to our case has proven to be more difficult than it might seem at first glance.

Nevertheless, we have seen fit to show a little of what we’ve managed to do so far, so as to lay the pathway for future developers.

A.1 Data setting and extraction

A.1.1 The railway

From the data in the map, we have compiled tables that approximate the essential set of values by intervals of 20 meters. The tables’ columns were then imported into Matlab, and, through one-dimensional lookup tables, the Simulink model can obtain their value in every instant from the position of the train $x$ (in meters). In order to compensate for the sometimes gross approximation made in the tables, the lookup tables are set to interpolate the exit value through polynomial, quadratic interpolation.
APPENDIX A. CALCULATIONS AND MODELING

A.2 Power requirements

A.2.1 Train Resistance and tractive efforts

The train resistance $W$ is the sum of all forces opposed to the driving movement, and can be separated into the following components:

- Rolling resistance $W_r$
- Curve resistance $W_c$
- Gradient resistance $W_g$
- Acceleration resistance $W_{ac}$

To overcome these resistances, the train’s propulsion must deliver equivalent tractive efforts

$$F = G_T \cdot w$$  \hspace{1cm} (A.1)
A.2. POWER REQUIREMENTS

$G_T$ being the weight of the train.

From $F$ and $v$, we will obtain the input necessary to look up the $F - v$ tables of the electric motors in the next section, making the appropriate deductions.

To calculate each separate resistance, we will choose to use the models commonly employed by Deutsche-Bahn:

### A.2.1.1 Rolling Resistance

For a passenger train, (according to Sauthoff)

$$w_r = 1.0 + 0.0025 \cdot v + 4.8 \cdot \frac{n + 2.7}{G_T/kN} \cdot 0.0145 \cdot (v + 15)^2$$  \hspace{1cm} (A.2)

$v$ being the train’s speed in kph, $n$ the number of coaches including the locomotive, and 15 being the addition for head wind. In tunnels, additions to the $v^2$ coefficient have to be taken into account.[!!!!]

### A.2.1.2 Curve Resistance

Curves cause transversal slipping under friction in the wheels;

$$w_c = \begin{cases} 
\frac{650}{R/m - 30} (N/kN) & \text{when } R \geq 300m \\
\frac{500}{R/m - 55} (N/kN) & \text{when } R < 300m 
\end{cases}$$  \hspace{1cm} (A.3)

In the Simulink model, this condition is represented by a switch.
A.2.1.3 Gradient Resistance

The gradient resistance in N/kN equals the gradient $s$ in per mille:

$$w_g = s = \tan \alpha \cdot 1000(N/kN)$$  \hspace{1cm} (A.4)

In the Lleida-La Pobla line, they do not go over 17\%.

Given that the tables already express the gradient in \%, no further processing is required.

A.2.1.4 $W_a$, the acceleration resistance

The acceleration resistance depends on the lineal and rotary inertia of the train, which is summarized as an allowance for rotating masses $\epsilon$:

$$w_a = \frac{a}{ms^2} \frac{g}{ms^2} \epsilon/1000(N/kN)$$  \hspace{1cm} (A.5)

$a$ being the train’s acceleration, and $g$ being the gravitational constant. This allowance can be worth from 1.08 to 1.12 for electric coaches, and from 1.15 to 1.30 for electric locomotives. Passenger trains’ accelerations have a typical value of 0.3 to 0.4 m/s$^2$.
A.3 Control And Drives

A.3.1 Power

A.3.1.1 Set Point

We have chosen to establish the acceleration as the "wish of the driver", so to speak, the equivalent of "stepping on the gas pedal", with speed and position derived from there.

\[ a \xrightarrow{\frac{1}{s}} v \xrightarrow{\frac{1}{s}} x \]

Figure A.7: \( v \) and \( x \) derived from \( a \)

A.3.1.2 Transitory Acceleration

Nominal power \( P_N \) is the one needed to maintain base speed \( v_1 \), according to UIC (called speed at full notching, in times of contractor control). At speeds higher than \( v_1 \), the power will be kept constant and equal to nominal power, and the motors will be operated with weakened field (unless it runs on commutator machines). Machines can reach a much higher power in starting mode (five minutes) than continuously (maintained over one hour or more).

A.3.2 Speed Limitations

The train’s speed may never exceed a certain limit:

A.3.2.1 Maximum speed due to curves

Due to the danger of derailing, the maximum theoretical speed attainable depends on the track gauge and the actual outer rail elevation:

In practice, however, the available speeds are set by stages, rather than defined point-by-point (See Fig A.9 and A.10).

A.4 Some gross estimations
APPENDIX A. CALCULATIONS AND MODELING

Figure A.8: $w_g$ from $s$ in Simulink

Figure A.9: Speed limits throughout the Lleida-La Pobla line, pt. I
### A.4. SOME GROSS ESTIMATIONS

Figure A.10: Speed limits throughout the Lleida-La Pobla line, pt. II

<table>
<thead>
<tr>
<th>Línia 206 (sentid Par)</th>
<th>De: LLEIDA-PINNEUS</th>
<th>A: LA POBLA DE SEGUR</th>
<th>Línia 206 (sentid Par)</th>
</tr>
</thead>
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<td>M</td>
<td>A</td>
<td>E</td>
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C.V.M. 2º GRUPO - Ed. 3059514

Page 1 of 1
Appendix B

Budget

In Table B.1, an estimation is made of the cost of making, based on estimates of the cost of hiring professional help to perform the different tasks, and that of the equipment, facilities and comforts necessary to perform them.

<table>
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<th>Human activities</th>
<th>Estimated Cost (€/h)</th>
<th>Total Hours</th>
<th>Total cost</th>
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<td>1600</td>
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<tr>
<td>Contacting sources and acquiring data</td>
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<td>Writing and Editing</td>
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Table B.1: Rough estimation of the project’s cost
Appendix C

Tables and Maps

See CD for the full table of the characteristics of the Lleida-La Pobla line for each 20 m, as well as the maps of the railway they were deduced from.