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Artificial Intelligence Applied to Evaluate Emissions and Energy Consumption in Commuter Railways: Comparison of Liquefied Natural Gas as an Alternative Fuel to Diesel

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Abstract: At present, there is a common effort to reduce the environmental effect of energy consumption. With this objective, the transportation sector seeks to improve emissions in all its modes. In particular, the rail transport industry is analysing various alternatives for non-electrified lines. These services are mainly carried out with diesel units. As an alternative to diesel fuel, in the present study the use of liquefied natural gas (LNG) in railway traction was analysed. A predictive model was developed and implemented in order to estimate the emissions impact of this fuel on different rail routes or networks. The model was fitted with real data obtained from pilot tests. In these tests, a train with two engines, one diesel and the other LNG, was used. The methodology was applied to evaluate the impact on consumption and emissions of the two fuels on a narrow-gauge commuter line. An improvement was observed in some indicators, while in others there was no clear progress. The conclusions that can be drawn are that CO_2 (greenhouse gas) operating emissions are lower in the LNG engine than in the diesel line; CO emissions are lower in the diesel engine and emissions of other pollutants (nitrogen oxide and particles) are higher in the diesel engine by several orders of magnitude.

Keywords: alternative fuel; liquefied natural gas; energy consumption; emissions; railways

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1. Introduction

The transport sector is responsible for a significant share of greenhouse gas emissions. In Europe, in particular, this value amounts to a quarter of all emissions [1]. This is why there is great concern to reduce these emissions. Railway companies are no stranger to this awareness. The transport sector is engaged in a process of reducing its carbon footprint through more efficient technologies [2].

However, the carbon footprint is not the only problem associated with transport emissions. The transport sector is one of the main sources of air pollutants that can cause a variety of health impacts, especially in urban and suburban areas. Nitrogen oxides (NO_x), particulate matter (PM), sulphur oxides, and carbon monoxide are all emitted from the exhausts of combustion engines. Exposure to these pollutants has both acute and chronic effects on human health, affecting different organs and systems, and is associated with increased mortality [3,4]. So-called nitrogen oxides include both nitrogen monoxide (NO) and nitrogen dioxide (NO_2) and have a wide range of effects on human health (inflammation of the respiratory tract, disorders of organs such as the liver or spleen, or of systems such as the circulatory or immune system, which in turn lead to lung infections and respiratory failure) and on the environment (acidification and eutrophication of ecosystems, metabolic disorders, limitation of plant growth). Acidification processes can also affect buildings [5]. In addition, NO_x contributes secondarily to the formation of inorganic particulate matter (as precursors of nitric acid, HNO_3, and thus nitrate, NO_3- in particulate matter) and also acts as a precursor for the formation of ozone (O_3) and other photochemical pollutants, which can aggravate health and environmental impacts and lead to climatic effects. Sulphur dioxide (SO_2) causes eye irritation, coughing, mucous secretion, asthma, and bronchitis [6]. Exposure to high levels of PM is associated with increased mortality and hospital admissions for respiratory and cardiovascular diseases worldwide [7].

Rail transport is undergoing renewal with improvements in both rolling stock and infrastructure [8]. Therefore, investment in new technologies is essential in order to reduce GHG emissions and other air pollutants [9]. Emissions from the rail industry can be loosely grouped into the following major categories: energy consumption of the vehicles; occupancy levels and service frequency; electricity production; rolling stock technologies; the manufacture, construction, and use of infrastructure; and modal shift and factoring in demand generation [10].

In recent decades, the railroad has been powered by electric or diesel locomotives. In society, there is an idea, accepted as an axiom, that electric traction is more environmentally friendly than diesel. Nevertheless, if the whole supply chain is considered, some studies deny this assertion [2,11]. These results hold if well-to-wheel surveys are performed [12]. Eco-efficiency studies have also been used in the evaluation of diesel traction in railroads [13].

Over the past two decades, the rail industry has increasingly investigated the field of alternative fuels, with the aim of finding substitutes for diesel. This work is aimed at both reducing emissions and minimizing operating costs. [14]. For example, the Clean European Rail-Diesel project analyses the various traction alternatives for railways [15].

Alternatives to existing fuels include biodiesel [16], thorium [17], natural gas [18], and hydrogen [19]. Of these, natural gas is the most promising [20]; it can be used in both gaseous (compressed natural gas, CNG) and liquid form (liquefied natural gas, LNG). Emissions from engines using natural gas have been the subject of numerous studies including [21–27].

In the recent literature there are a variety of studies on the use of LNG in rail traction only in heavy-duty locomotives. For instance, in Russia [28–31], Canada [32,33], and the USA [34–39].

The different studies reveal that natural gas is a technically viable alternative to diesel fuel. In addition, it has been shown to significantly reduce pollutant emissions, such as particulate matter and NO_x. Given that these emissions have a significant impact on health when they occur in urban environments, the application of this type of fuel in diesel commuter trains is being considered.

The previous experiences have been with freight locomotives; therefore, in the present study, the use of LNG in diesel multiple units was considered for the first time. In order to evaluate the impact that the application of this fuel would have on the current network, the methodology described in this paper was proposed.

This methodology was applied in Spain, where in 2017 the Spanish operator RENFE began pilot tests of a self-propelled passenger train powered with liquefied natural gas (LNG). The tests took place on a narrow-gauge network. An engine powered by LNG replaced one of the two diesel engines used on the two-coach train, with the second diesel engine used to compare the results of operation (emissions and consumption) with diesel and LNG traction [40]. The first step was to analyse the rolling resistance of the railway composition [41]. In addition, pilot tests made it possible to obtain the traction performance of the various powertrains [42]. This allowed accurate monitoring of the tested rail network [43] by means of vehicle instrumentation [44] to analyse driving conditions and emissions with the same techniques as used for other types of land vehicles [45].

This paper presents the development of a methodology for the comparison of the emissions of a railway transport multiple unit under different running conditions. A predictive model based on artificial intelligence was developed and implemented. This model was refined and validated with the results of the pilot tests. The final model makes it possible to extrapolate to other rail routes or networks.

The application of the proposed methodology makes it possible, once the study units have been experimentally characterised, to apply the parameterised predictive model to any line that is able to incorporate different types of powertrains. These predictive studies represent a significant saving in time and costs as it is not necessary to carry out tests with real vehicles on the networks to be analysed [46]. It also has the advantage of obtaining operational results without having to alter the traffic conditions of the lines and networks under study.

The remainder of this paper is organized as follows. Section 2 describes the diesel multiple unit and the LNG transformation to diesel and/or LNG traction. Additionally, the sensing of the vehicles and the pilot testing program to validate the dynamic model is presented. In Section 3 the implementation of the proposed methodology on a specific commuter line is detailed. Section 4 presents the conclusions.

2. Materials and Methods

To carry out the pilot test, a RENFE series 2600 diesel multiple unit (2 motor coaches, M-M configuration) was used. RENFE Series 2600 (Figure 1) are railway vehicles that are used as suburban trains on non-electrified lines. The 2600 series vehicles were built between 1966 and 1974 by MAN-MMC-Ateinsa. These vehicles have subsequently been transformed (1999–2001) by FEVE (at present the Spanish railway company Renfe Ancho Métrico) and CAF-Sunsundegui. They have a capacity of 48 + 48 seated seats. The top speed is 80 km/h. The main characteristics are listed hereunder:

- Gauge: 1.000 m (narrow)
- Weight: Odd unit (26,420 kg) + even unit (27,040 kg) = 53,460 kg in total
- Length: 35.888 m
- Width: 2.565 m
- Height: 3.655 m

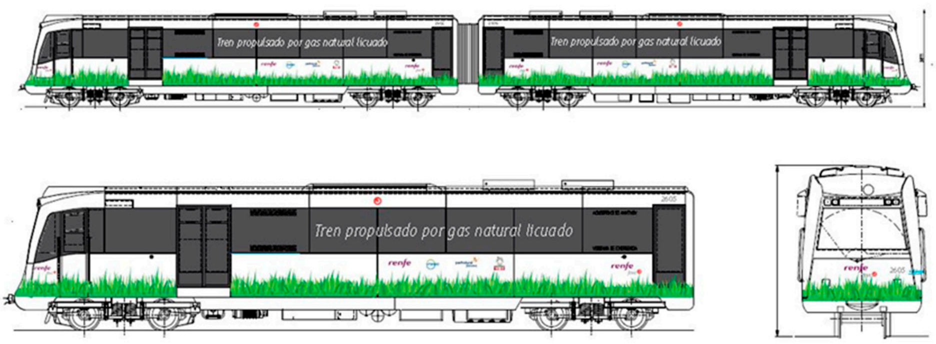


Figure 1. Diesel multiple unit 2600 (https://www.vialibre-ffe.com/noticias.asp?not=20940, accessed on 24 June 2021).

Each coach has a diesel engine, a Volvo THD 101 GB with 6 horizontal, in line cylinders. The cylinders have a bore of 120.65 mm and a stroke of 140 mm. With a rated power (according to ISO1585) of 163 kW@2200 rpm, and a rated torque of 780 Nm@1400 rpm, this engine fulfils emission level limits according to ECE reg 24-02, ECC 72/306.

One of the coaches underwent a conversion to LNG. The original diesel engine was replaced by an exclusive factory-built natural gas engine manufactured by CUMMINS, a Cummins ISL GeEV280 engine, while retaining the original diesel engine of the second coach. This LNG engine is an 8.9 L mid-range engine with SCR (selective catalytic reduction). This engine complies with Euro 5 and ADR80/3 emissions regulations. Some specifications are listed below:

- Type: 4-cycle, in line, 6 cylinder, turbocharged/charge air cooled
- Bore and stroke: 114 × 145 mm
- Compressions ratio: 16.6:1
- Oil system capacity: 27.6 L
- Dry weight: 706 kg
- Power (according to SAE J1995): 209 kW@2000 rpm
- Torque: 1700 Nm (1300–1400 rpm)

The emission level of this engine is Euro EEV. EEV stands for enhanced environmentally friendly vehicle. EEV is specific to heavy duty truck or bus engines and corresponds to Euro V emission levels but with lower limits for hydrocarbons and smoke number.

The Cummins ISL GeEV 280 has a 28% higher rated power and a 56% higher maximum torque when compared to those of the Volvo THD 101GB (Figure 2).

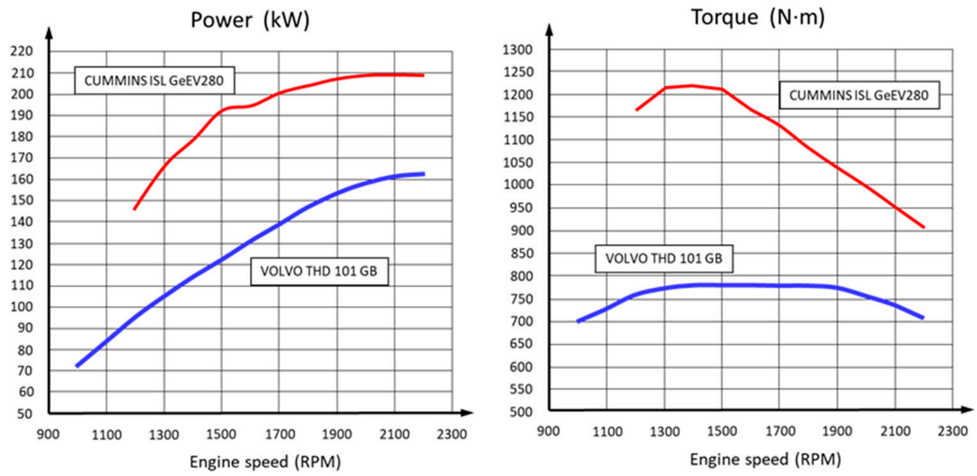


Figure 2. Engine characteristics curves.

Two Dewar-type LNG storage tanks were installed to ensure a range equivalent to 400 km, as well as the adequacy of the control, safety, and auxiliary systems to ensure the perfect integration of the changes introduced and allow their operation in parallel with the diesel unit.

Every coach is equipped with a Voith D 506 hydraulic transmission. It is a fully automatic hydrodynamic-mechanical transmission, which includes a hydrodynamic torque converter, a differential gear unit, and an epicyclic gearbox equipped with multi-disc brakes for the selection of the forward and reverse gears.

At lower speeds (<40 km/h), the differential gear unit distributes the power transmitted from the engine between one hydraulic power path and one mechanical path, whereby the power transmitted into the hydraulic path diminishes progressively with increasing vehicle speed. At higher speed, the input power is transmitted purely mechanically. Therefore, in the mechanical operation range, the transmission has the same (negligible) transmission losses as any mechanical change-speed gearbox. As both engines have the same type of transmission, both engines have the same operation points (torque and rotational speed requirements) for a given driving situation.

In addition, the multiple unit was installed with instruments and monitored in order to obtain all the parameters, both operational and environmental, necessary to refine and validate the predictive model. AVL Ibérica, S.A performed on-board emissions measurements with a portable emissions measurement system (PEMS) and different modules, and the recorded variables are listed below:

- Garmin (16x) GPS: Latitude, longitude, and elevation
- Weather Station: Pressure, temperature, and humidity of ambient air
- AVL EFM 495: Exhaust mass flow
- DG DPA5 J939: J1939 CAN parameters

- AVL Micro Soot Sensor 483: The AVL Micro Soot Sensor is a system for continuous and transient measurement of soot concentrations (mg/m^3) in exhaust gas from internal combustion engines.
- AVL Gas PEM HD 493: this is a portable emission measurement system (PEMS) that monitors THC (total hydrocarbons), CO, CO_2, NO_2, and O_2% concentrations within the exhaust gas of internal combustion engines of any kind.

Additional sensors were included, such as a fuel flow meter, (gas flow meter or diesel flow meter), accelerometers, data loggers. Measurement resolution was 10 Hz for all the parameters except for those related to the GPS, which were at 2 Hz. All the devices used during the subject measurements were compliant with the requirements described in EU 2017/655.

After a phase of static tests and once the corresponding circulation and testing authorizations had been obtained, the unit was tested in Northern Spain. Operational tests were conducted between the stations of Trubia and Figaredo, belonging to the RENFE (narrow-gauge) “Trubia-Collanzo commuter line”. The operational testing phase was completed in 2020, after completing a significant number of operating hours and about 4000 km travelled. An experimental program test was performed in order to refine and validate the predictive model. This program was carried out on an approximately 2.9 km section of line between Viesca and Palomar stations (Figure 3). During the measurement time, the test track was traversed several times in both directions.

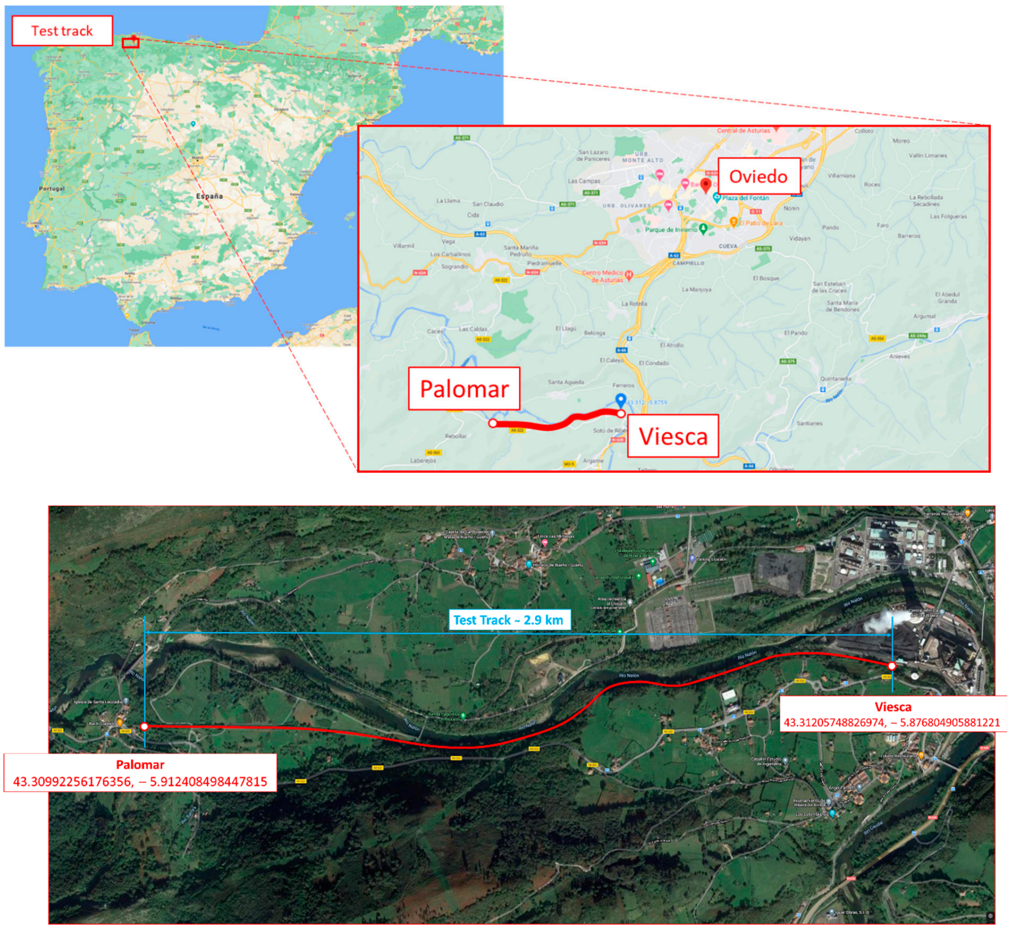


Figure 3. Pilot test track.

The experimental program test followed these steps:

1. Characterization of passive resistances, both on a straight track and on curves;
2. Evaluation of inertial and mass factors and parameters;
3. Evaluation of actual acceleration and braking performance;
4. Execution of consumption and emission tests at various speeds and accelerations; and
5. Characterization of the LNG and diesel powertrains.

Once the diesel and LNG engines models had been refined and validated, an intelligent predictive model (IPM) was developed. For this, artificial intelligence techniques were applied based on the available operating variables, the design of the route, the environmental conditions, and the load of the vehicle.

Two software modules were developed: the mapping generation module and the predictive model. In the first module, machine learning algorithms were used to obtain a map of the engines, which made use of the measurements collected on the test track. In the second module, a commercial route was simulated.

The mapping generation module uses neural networks to learn a model of the instantaneous consumption and emissions of each engine, taking torque and engine speed as inputs. The instantaneous consumptions are derived from fuel composition and on-board emissions measurements taken with a portable emissions measurement system (PEMS), as described in the preceding section.

The commercial route is defined by its elevation and profile projections, the reference speed on each section, and the stations. The predictive model begins by determining the speed profile that allows the route to be travelled in the shortest possible time, stopping at each station, and without exceeding the reference speed on each section or the maximum and minimum permitted accelerations. Then, given the mass of the vehicle, a mathematical model of the gearbox, the driving resistances, the slope and the losses in auxiliary consumption, the torque, and engine revolutions needed to cover the route are determined. If the maximum torque at the required engine revolutions is insufficient at a point along the route, the acceleration at that point is reduced and the speed profile is recalculated with the new constraint. The process is repeated until the speed profile is physically achievable. Finally, the torque and angular velocity values calculated for each point on the circuit are fed into the model developed in the first module to obtain an estimate of the instantaneous and cumulative consumption and emissions over the commercial route.

In the predictive model it was decided that the most probable set of actions of the driver in each section consists of the following:

- Accelerating at 0.50 m/s^2 until reaching the maximum speed on each section; and
- Calculating the point at which it should decelerate at 0.50 m/s^2 until the vehicle stops at the station or stopping point.

To validate these assumptions, the Figaredo–Collanzo section was traversed on a train in commercial traffic conditions in both directions, recording the speeds at each point with a GPS to validate the simulation of the driver's actions.

Thus, the model provides a prediction of the variables related to the consumption and emissions of the vehicle. The main use of this IPM is to quantify the differences in consumption, contamination, and cost in different future scenarios of LNG implementation. The IPM allows conditions to be extrapolated and simulates changes in vehicle emissions in the face of varying routes and diverse environmental conditions. With these tools, a framework is deployed to carry out life cycle analyses, with the estimation of GHG emissions extended to an entire railway transport network (local, regional, national, or international).

The flow chart of the methodology is shown in Figure 4. It can be seen how the predictive model is based on the values of the pilot test measurements. This allows values to be given to the parameters that characterise the model. These parameters are related to the forward resistances of the units, the performance of the traction motors, and the characteristics of the railway track. In addition, the driver's actions have been parameterised according to the traffic restrictions. In each case study in which this methodology is applied, this set of parameters must be obtained in the same way to improve the accuracy of the consumption and emission results predicted by the model.

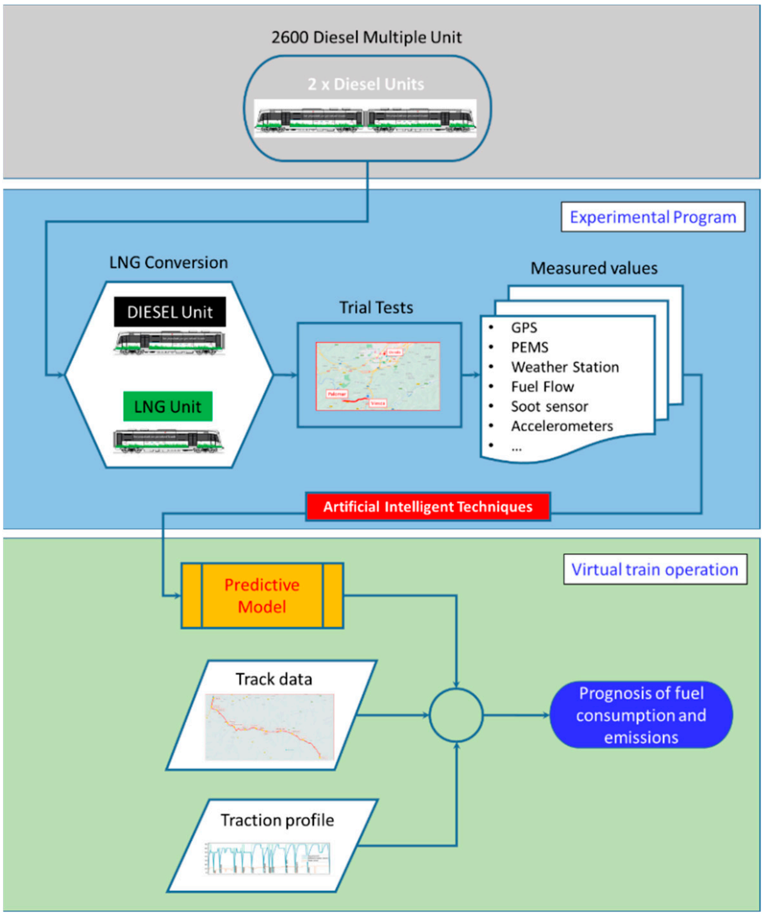


Figure 4. Map with the track and stations.

Therefore, the results will depend directly on the environment that is simulated with the predictive model. In the case of wanting to analyse the traffic flow of the composition tested in the pilot tests on another line, the model must know the route of the line, the stops, and the traffic restrictions. In the case of lines running in both directions, the results shall be obtained by simulating both traffic flows, in order to take into account the track profile.

Description of the Intelligent Predictive Model

The purpose of the IPM module was to extrapolate the fuel consumption and emission measurements taken on the test section to a route with an arbitrary layout. This extrapolation is carried out in two phases:

1. Estimation of the speed profile of the circuit, given the layout and elevation of the new route and the properties of the engine (maximum torque curve, efficiency of the different elements of the powertrain).
2. Prediction of consumption and emissions on the new route, given the speed profile calculated in the previous step. This is done by using a consumption and emission model for each pollutant as a function of the engine operating point (torque and engine speed).

The estimation of the speed profile is based on the maximum speeds on each section, the designated stops, and the legal limits for acceleration and braking. A driving model is used which consists of staying as long as possible at the maximum speed of each section and performing constant acceleration or deceleration manoeuvres at the points closest to each change of maximum speed setpoint. In cases where the slope of the circuit is steep and the powertrain is not able to supply the torque required to maintain maximum acceleration, the acceleration is reduced to a feasible value. The route is discretised into small segments, where the acceleration can be considered to be constant. To obtain the accelerations in each section, a quadratic sequential programming problem is solved for each of them [47]. The time in which the segment is travelled is minimised, including the restrictions to the legal limits of acceleration and braking, and that the engine torque is less than the maximum torque at the corresponding speed. The engine torque is determined on the basis of the tractive effort required to overcome the inertia forces, the gradient, and the drag, taking into account the efficiency of the transmission, the operating mode of the gearbox (hydraulic or mechanical), and the auxiliary consumption of the unit (compressors, air conditioning, alternator, etc.).

Once the speed profile of the route has been determined, the operating point of the engine in each of the sections is calculated and the fuel consumption is obtained by accumulating the predictions obtained through the BSFC (brake-specific fuel consumption) curves of the engine and the emissions of each pollutant through the brake-specific emissions curves. These curves were been provided by the manufacturer, but they were determined experimentally from measurements on the test circuit. Figure 5 shows one such curve, which relates the total emissions of the LNG engine in kg/h to the operating point of the engine, defined by the pair (speed, torque), in revolutions per minute and N/m, respectively. The left part of the figure shows the raw data measured on the test section. The middle part shows the prediction of an XGBoost regression model [48] trained on the left-hand data, and finally, the right-hand part shows the brake-specific emissions curves of that engine, calculated as the contour lines of the model shown in the middle part.

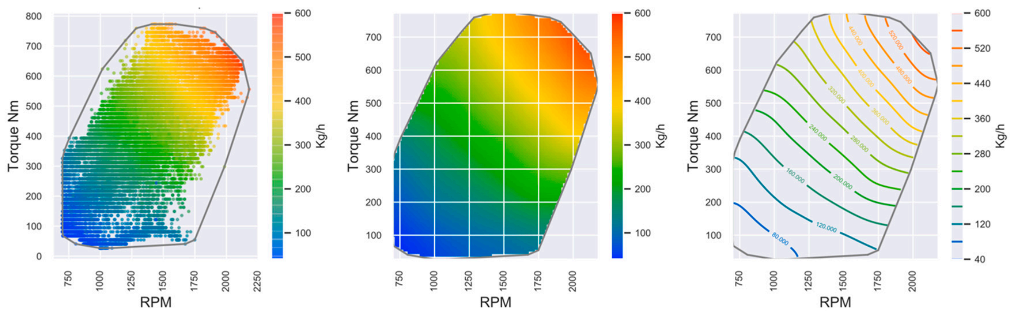


Figure 5. Estimation of total LNG engine emissions as a function of the operating point.

3. Results

The proposed methodology implements the validated predictive model of the 2600 units on the section between Figaredo and Collanzo. This narrow-gauge RENFE track passes through a well populated area, whose history of coal mining and iron and steel making activities has led to it becoming very sensitive to emissions and pollutants. The proposed methodology was put forward to evaluate the effect of a potential change in the fuel used on commuter trains, from traditional diesel to alternative LNG solutions.

The result sought was the evaluation of emissions over the study section, both globally and in detail at each point of the network, to correlate them with the presence of densely populated areas.

A detailed profile of the railway infrastructure is available, with information on both inclines and curves, train stations, and other stopping points. The commercial speed profile established for the section in both directions of traffic and the scheduled timing (Figure 6) are also available. The railway section studied includes a total of 13 stations, including the two at the ends of the route (Figure 7).

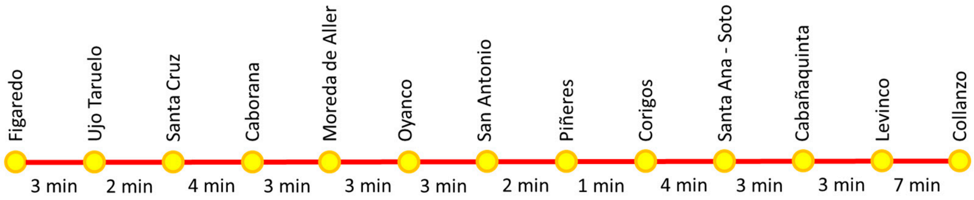


Figure 6. Stations and scheduled travel times on the analysed section.

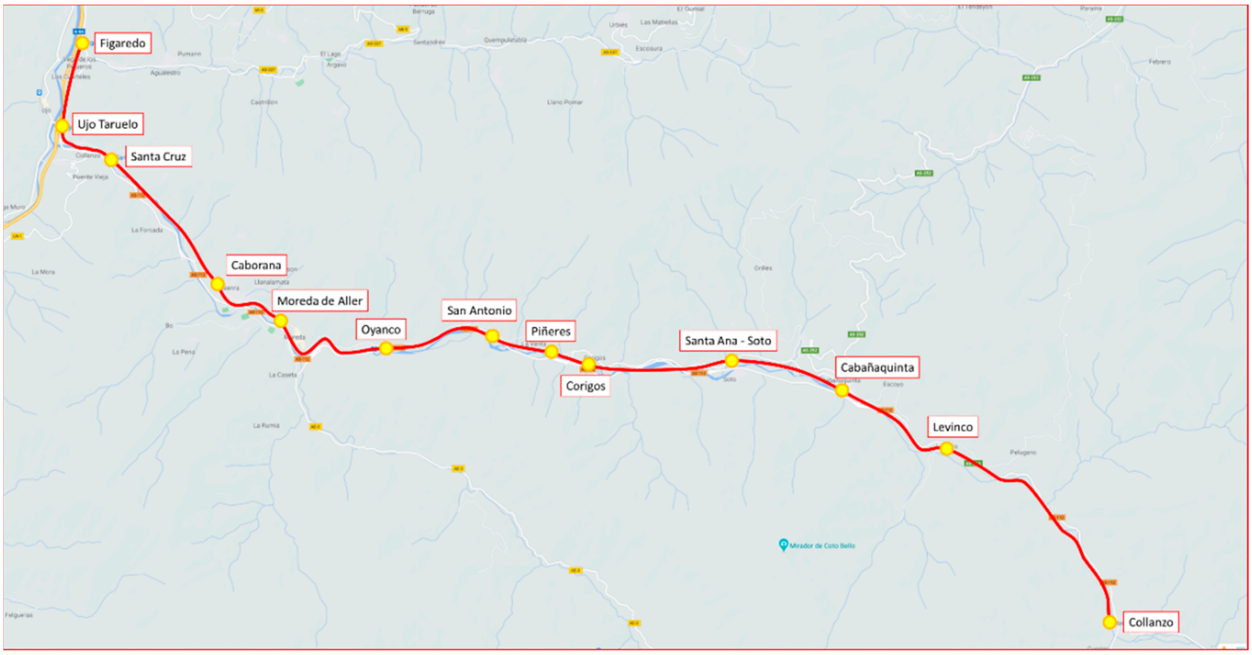


Figure 7. Map with the track and stations.

With all this information, the driving manoeuvres carried out by the railway multiple unit are defined to comply with all the restrictions imposed on the transport service. This is shown in Figure 8.

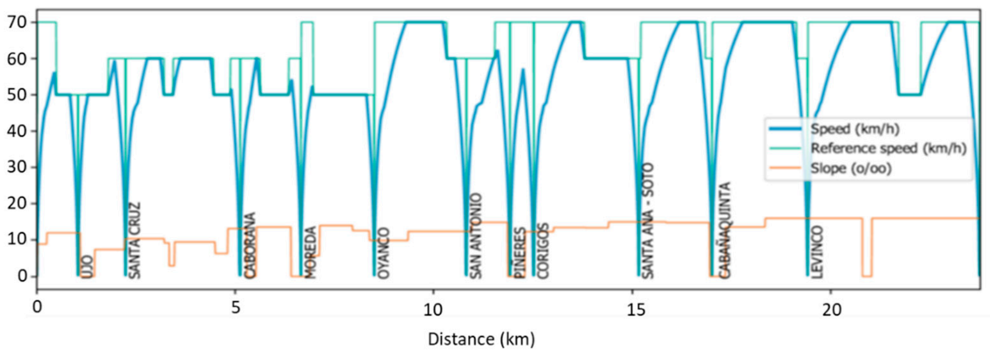


Figure 8. Traction profile. Includes reference speed, actual speed, and track gradient (slope).

The methodology presented processes all this information to obtain diverse results, as shown in Figure 9.

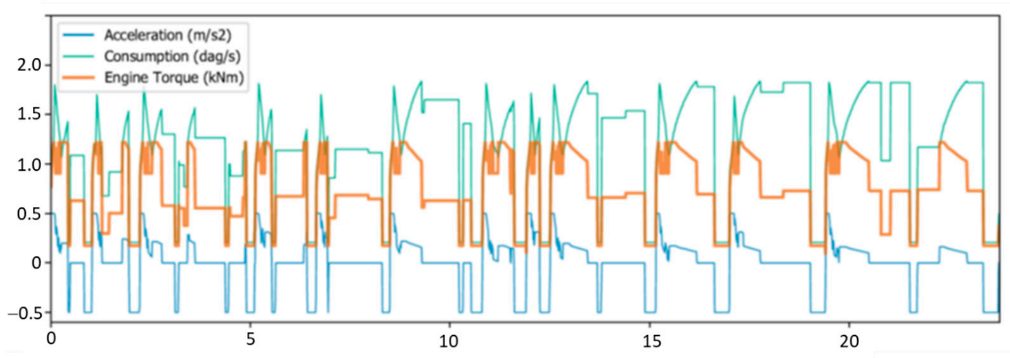
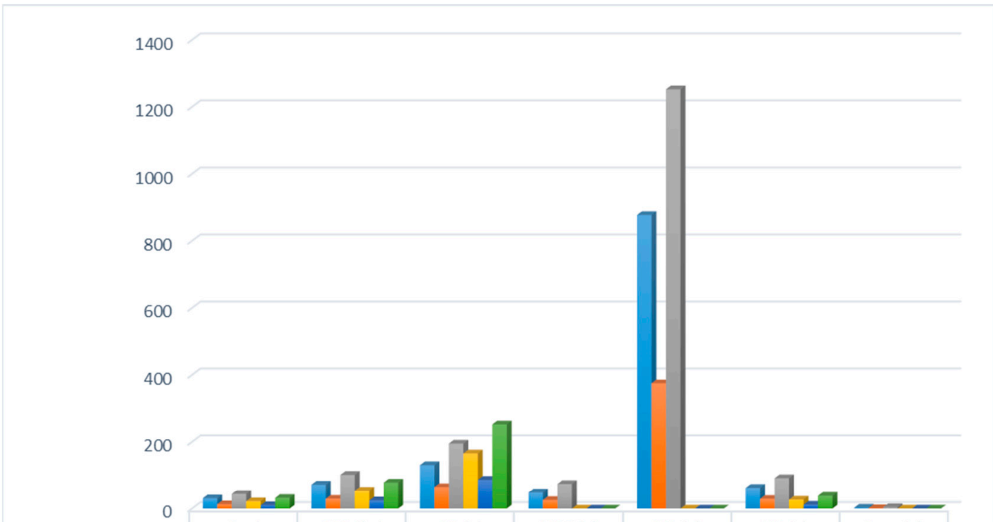


Figure 9. Kinematic and powertrain variables versus distance with the LNG engine.

According to the elevation profile, the railway line has a gradient (Figure 8). If the units are travelling from Figaredo to Collanzo (outward, Figure 9) there is an incline that causes more fuel to be consumed (and emissions produced) than on the return, in the opposite direction. This can be seen in Figure 10.



	Fuel	CO2 (kg)	CO (g)	NO2 (g)	NO (g)	HC (g)	Soot (g)
Diesel Outward	31.0	71.95	130.51	48.52	877.57	62.30	2.77
Diesel Return	12.90	29.42	64.68	25.53	375.12	28.94	1.32
Diesel Total	43.89	101.37	195.18	74.05	1252.68	91.24	4.09
LNG Outward	21.99	53.81	165.70	0.00	0.01	26.92	0.01
LNG Return	10.10	24.65	86.60	0.00	0.00	11.58	0.01
LNG Total	32.09	78.45	252.30	0.00	0.02	38.49	0.01

Figure 10. Fuel consumption and emissions on the upward section from Figaredo to Collanzo (outward) and downward from Collanzo to Figaredo (return). The units of fuel consumption for the diesel engine are expressed in l, and for LNG in kg.

The proposed methodology, applied to the section studied, allows both fuel consumption and emissions to be obtained in detail. These values were obtained on an averaged basis for the entire route of the line in both directions of circulation. These results, expressed in units per kWh, per km or per hour, are shown in Table 1. The units of fuel consumption for the diesel engine are expressed in l, and for LNG in kg.

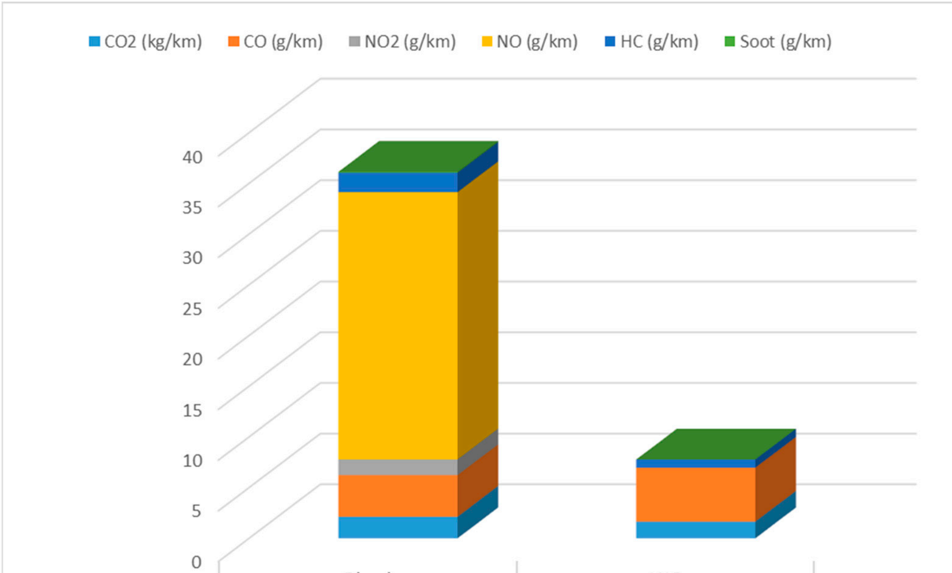
Table 1. Fuel consumption and emissions.

	Fuel	CO_2 (kg/kWh)	CO (g/kWh)	NO_2 (g/kWh)	NO (g/kWh)	HC (g/kWh)	Soot (g/kWh)
Diesel	0.26 L/kWh	0.59	1.14	0.43	7.32	0.53	0.02
LNG	0.18 kg/kWh	0.45	1.44	0.00	0.00	0.22	0.00
	Fuel	**CO_2 (kg/km)**	**CO (g/km)**	**NO_2 (g/km)**	**NO (g/km)**	**HC (g/km)**	**Soot (g/km)**
Diesel	0.92 L/km	2.13	4.10	1.56	26.34	1.92	0.09
LNG	0.67 kg/km	1.65	5.31	0.00	0.00	0.81	0.00
	Fuel	**CO_2 (kg/h)**	**CO (g/h)**	**NO_2 (g/h)**	**NO (g/h)**	**HC (g/h)**	**Soot (g/h)**
Diesel	33.92 L/h	78.34	150.84	57.22	968.09	70.51	3.16
LNG	26.15 kg/h	63.93	205.61	0.00	0.01	31.37	0.01

The analysis of these results shows that, although of the same order of magnitude, diesel consumption (in litres) is always higher than LNG consumption (in kg). This can be seen both in the evaluation by energy (kWh), by distance travelled (km), or by driving time (h). Table 1 also shows the CO_2 emissions, which are proportional to the amount of fuel consumed and show the same trend as indicated for fuel. CO_2 emissions are higher for the diesel traction analysed compared to LNG. These results are reversed for CO. For this pollutant, the LNG traction analysed shows worse values than diesel engines, mainly due to the type of combustion and the treatment of the air-fuel mixture and exhaust gas management. These values could differ, especially when analysing a diesel vehicle with more advanced technologies. They are practically zero for LNG as far as nitrogen oxides and unburned hydrocarbons are concerned. This is justified by the existence of sensors and catalysts that minimise these emissions. This is because the LNG engine has a higher technological level and meets higher environmental requirements. The very nature of the fuel in the case of the LNG engine means that soot emissions are almost negligible in this case, in contrast to the high values obtained in the case of diesel.

For a comparison of the two traction fuels in the study section, it is interesting to present the aggregated emissions data for the two engines (diesel and LNG). Figure 11 shows the averaged values per km of line travelled. It can be appreciated that the total emissions of the diesel engine are higher. This value of the total emissions is clearly influenced by the high emissions of NO. This is due to the fact that there is no post-treatment of the exhaust gases for the catalytic reduction of nitrogen oxides. This is a fundamental difference between the successive evolutions of diesel engines in terms of compliance with the different regulations both nationally and internationally.

The proposed methodology makes it possible to determine both consumption and emissions at each point along the route. This is of especial interest in the correlation of these values with the population density of the areas through which the analysed multiple unit travels. Figure 12 shows, by way of example, the values of solid particles (soot) emitted by the diesel engine at each point of the study section.



	Diesel	LNG
Soot (g/km)	0.09	0
HC (g/km)	1.92	0.81
NO (g/km)	26.34	0
NO2 (g/km)	1.56	0
CO (g/km)	4.1	5.31
CO2 (kg/km)	2.13	1.65

Figure 11. Averaged values of emission per km.

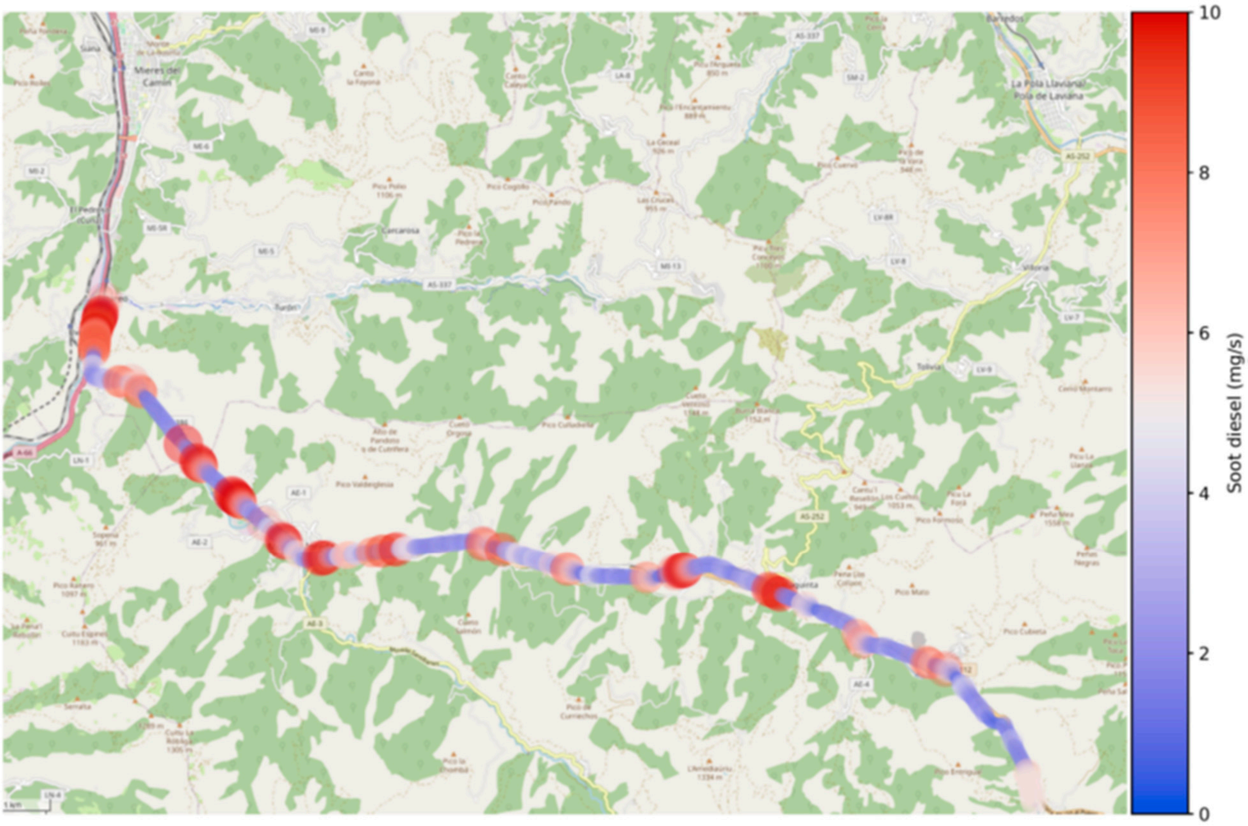


Figure 12. Soot emissions: diesel engine case.

4. Conclusions

To explore the possibility of replacing diesel as the fuel for rail vehicles, the use of LNG was considered. Within the framework of a public-private consortium, the Spanish operator RENFE conducted a pilot test of a self-propelled passenger train powered by LNG. The tests have allowed the fitting and validation of a smart predictive model to evaluate and compare the operation with traditional fuel (diesel) and with LNG. This model was applied to a study section of track, over which both consumption and emissions were analysed under real conditions of commercial operation. The following conclusions were drawn:

Instantaneous consumption: The LNG engine has a lower instantaneous consumption (measured in kg/s). CO_2 emissions were precisely measured, and the instantaneous emissions of both engines were similar. As the emission factors were close to each other (2.79 kg CO_2 per litre of diesel, versus 2.75 kg CO_2 per kg of LNG) the measurement data for CO_2 emissions support the previous conclusion that fuel consumptions are lower in LNG engines.

Instantaneous greenhouse gas emissions: CO_2 emissions are lower in the LNG engine. The methane emissions from the LNG engine are lower than the hydrocarbon emissions from the diesel engine. Methane emissions from the LNG engine do not constitute a significant emission of greenhouse gases. Venting was not taken into account in this analysis, since the operation of refuelling and maintenance of the vehicle has yet to be defined.

Instantaneous emissions of pollutants: Diesel engine NO, NO_2, and particulate matter emissions (soots) are higher than the corresponding LNG engine emissions in all operating scenarios, and by several orders of magnitude. In fact, the emissions of nitrogen oxides and particles from the LNG engine were negligible. The CO emissions from the Diesel engine were lower than the emissions from the LNG engine.

The conclusions that can be drawn coincide with those expressed for the instantaneous data: (1) CO_2 (greenhouse gas) emissions are lower in LNG engines than in diesel powertrains, in the absence of methane venting considerations, (2) CO emissions are lower in the diesel engine, and (3) emissions of pollutants (nitrogen oxide and particles) are higher in the diesel engine by several orders of magnitude.

This study investigated the effect of fuel replacement on a non-electrified rail network. Pilot tests carried out on a train powered by both a diesel and an LNG engine were used to fit a predictive model of consumption and emissions. A methodology was proposed and implemented for the comparative evaluation of consumption and emissions with diesel or LNG powertrains. The effect under commercial operating conditions can be inferred. The use of LNG as a fuel leads to improvement in some indicators, while other values do not show significant improvements.

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