

Article

Methodology for the Estimation of Electrical Power Consumed by Locomotives on Undocumented Railroad Tracks

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Abstract: The energy consumption estimation of a locomotive for a particular route is important for the selection of a locomotive technology, the improvement of the energy management system, the evaluation of the locomotive's potential energy generation, among others. The methodologies reported in the literature usually assume that the information of the railway track is available; however, in some cases, the track information is incomplete, not available, or the route is still in a planning stage. Therefore, this paper proposes a methodology to estimate the energy consumption and the potential energy generation of a locomotive when the railway track information is not available or incomplete. The methodology begins by extracting the main technical information of the locomotive to be analyzed. Then, the route is traced on Google Earth with steps of 100 m and the obtained information is processed to generate the longitude, latitude, elevation, and distance of the points along the route. From such information, it is possible to generate the slope and curvature profiles, while the speed profile can be obtained from the track operator or the regulations of a specific country. With that information, it is possible to estimate the equivalent power of the locomotive at each point of the route to finally calculate the consumed energy. The proposed methodology is validated with two case studies. The first one compares the results with a methodology available in the literature for the same route and locomotive, while the second case shows the applicability of the proposed methodology for a route without information.

Keywords: locomotive; energy consumption; energy generation; estimation; railway track geometry



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1. Introduction

Worldwide railway systems have promoted technological, social, economic, and industrial progress since the age of steam propulsion [1], due to the significant reduction in travel times and increment of the transported load capacity. Locomotives are the key elements in a railway system; therefore, the selection of a locomotive for a particular railway line, or the replacement of an obsolete locomotive, requires the estimation of the energy consumption considering the track geometry and the main characteristics of the particular locomotive [2,3]. Such energy consumption estimation can be used to compare different locomotives for a specific application, estimate the emissions of greenhouse gases, identify the technology that best suits a particular railway track, and plan new railway routes [4].

Although it is a relevant research focus, few works in the state of the art report a detailed analysis to perform the energy consumption estimation of a locomotive. These works can be divided into two groups, the first one corresponds to the methods based on historical

data, resulting from gathering the information of trajectories traveled with operating trains; while the second group corresponds to the methods based on information from railway infrastructure and locomotives, which relate the information to obtain an approximation of the consumption.

Regarding the first group, it is worth mentioning that few countries have a reliable database based on measurements of the condition of their railways and locomotives, which can be used to design a road map for the upgrading of their railway infrastructure [5]. This represents a problem when calculating the energy consumption of a railway system since, for historical-data-based methodologies, such as regressions using neural networks or fuzzy logic [6], it would not be possible to have a reliable database to feed the mathematical models. A particular case of historical-data-based methodologies is China, which estimates its energy consumption on trajectories based on data collected from different railway companies [7], facilitating statistical regressions with minimal errors. In addition to energy consumption calculation methodologies, other research areas, with an environmental impact focus, also require information about the railway and the trains when designing their calculation methodologies in terms of environmental pollution [8]. Such is the case of [9], where the authors described an effort of more than eight years for the collection of data for operating locomotives in the Brazilian railway system, exposing the problems of acquiring the necessary information to estimate their environmental indicators.

Methodologies based on historical data denote previously known data about the analyzed route. Such information is retrieved from databases built by the railway systems themselves, which have a technological infrastructure to gather information on each trajectory such as track condition, speeds, accelerations, times, among others. For example, in [10], the main contribution was to optimize the energy consumption for a mountainous trajectory by implementing an energy management system with batteries. Among the several important results reported, the author mentioned that the railway data were taken from a database provided by a railway company for the trajectory between Zagreb and Split, Croatia. Due to the information provided by the railway company, years later, the paper reported in [11] described an energy analysis for the Lika-Senj region with the same purpose of reducing energy consumption. Both works focused on simulating and estimating the electrical performance of the batteries through a MATLAB/Simulink model, which did not describe the design or the information required to estimate the energy parameters. In addition, the reported results were not compared with field experiments, since their main contribution lay in adding batteries to locomotives that did not have such technology yet.

Moreover, in the work presented in [12], the authors proposed to estimate the energy consumption and used it to calculate economic indicators, to reflect the impact generated from a strategy to reduce energy consumption and, consequently, to reduce the economic impact. This extensive work proposed a neural network to manage a DC microgrid of motors, batteries, and other electrical loads. The case study and its results were based on railway information published by [13], in which the collaboration of the French railway network was highlighted. Such information about the railway provided by the company served many other authors as a database to feed the energy consumption models for the proposed locomotives [14]. Additionally, it is important to mention that this work did not include experimental results.

On the other hand, the energy consumption estimation methodologies based on railway track information require detailed data from the railway track and the locomotive for trajectories without historical data of speeds, accelerations, times, etc. For example, to optimize fuel consumption in the locomotives of the Israeli railway system, the work proposed in [15] described an optimization technique that again required railway information. Although in this work they relied on Google Maps to highlight the route and showed an elevation profile of the studied trajectory, it was not explained if this information was obtained by some methodology to extract information from the map or if it was retrieved from some database.

Nevertheless, there are alternatives to calculate this energy consumption, through the characterization of the railway and the locomotive moving along it. To achieve this, it is necessary to perform an analysis using Newton's second law, which allows us to know the mechanical stresses around the locomotive; thereby, it is possible to estimate the power required to move the train at each point of the trajectory [16]. This methodology requires technical information about the locomotive, such as tractive effort, braking effort, maximum speed, among others. Likewise, it is necessary to know the characteristics of the railway to consider the opposing forces to the movement of the locomotive, such as the slope, curvature radius, and track gauge [17–20].

Such is the case of the work proposed by [21], which estimated the energy consumption of a locomotive in the Cartagena–Albacete trajectory of the Spanish railway system; to achieve this, the authors gathered information from the locomotive and the technical profile of the track of this path. Although this way of calculating energy consumption requires less information based on experience than the methodologies based on historical data, it still depends on information retrieved from databases, experimental measurements from the railway operators, or from companies in the railway sector that have at least mapped their trajectories. These characteristics restrict the application of this type of methodologies to railway systems that do not have technical information on their tracks.

Based on the state of the art, it is evident at this point how the works reported so far require information provided by the companies managing the railroads along with the locomotives operating on them. Otherwise, if such information is not provided or does not exist, it is not possible to estimate the energy consumption of a locomotive based on the methodologies analyzed in this section since, as previously reported, those methodologies require the trajectory information to obtain their results. It is worth noting that some software tools such as Google Earth [22,23] or GPS Visualizer [24] can be used to trace the railway track and obtain the latitude, longitude, and elevation of multiple points along the track. However, these tools do not provide the curvature, slope, and speed profiles required to implement the energy consumption estimation methodologies based on the railway track information. Other tools, such as the one introduced in [25], estimate the curvature of different roads and use a color scale to classify the curves from “moderate twisty” to “very twisty”. Nevertheless, this tool cannot be used to generate the curvature profile of a railway track.

Hence, this paper proposes a methodology to estimate the power consumption of a locomotive when the railway geometry information is not complete or is not available at all. The methodology requires the main data from the locomotive, which can be obtained from its datasheet or the manufacturer documentation, and the main information about the railway features (elevation profile, curvature profile, and slope profile) is estimated from the latitude, longitude, and elevation of multiple points along the track. Moreover, if the speed profiles are not available, they are generated from the national and international regulations considering the maximum theoretical speed as a restriction. From these data, it is possible to apply Newton's laws to estimate the net force of the locomotive at each point of the track, which can be combined with the speed and the motor efficiency to determine the mechanical and electrical power. Then, the methodology estimates the time instant for each calculated electrical power to determine the consumed energy and the potential energy generation of the locomotive along the route. Therefore, the main contributions of this paper are: (1) a procedure to estimate the curvature, elevation, and slope profiles of the track when this information is not available or incomplete, (2) a procedure to estimate the maximum speed profile of a train considering the track geometry, and (3) a detailed procedure to estimate the locomotive mechanical and electrical energy consumed by the locomotive during its acceleration as well as the potential energy generated during its braking.

The rest of the paper is organized as follows: Section 2 shows the mechanical model of the locomotive to estimate the net force and power at each point, as well as the energy estimation; Section 3 introduces the proposed methodology focusing on the estimation of the railway track profiles; Section 4 introduces two case studies to validate the proposed methodology, and the conclusions in Section 5 close the paper.

2. Calculation of the Energy Consumption of a Locomotive

To estimate the energy consumption of a locomotive in a given time window, it is necessary to determine the effective force experienced by the locomotive (F_{tk}) and its speed (v) at each time instant. From those variables, it is possible to calculate the mechanical power of the locomotive (P) and then integrate such power to determine the mechanical energy consumption (E). In turn, E can be used to estimate the electrical energy required (E_d) and the potential energy that can be generated with a regenerative braking system (E_g). The following subsections describe the procedure used in this paper to calculate F_{tk} , P , E , E_d , and E_g .

2.1. Calculation of the Locomotive Effective Force

The first step is to analyze the interacting forces on the locomotive. For this purpose, Newton's second law is used at each point of a specific trajectory, along with the acceleration of the train and its total known mass. The free-body diagram of the locomotive at a specific position is shown in Figure 1, where the interacting forces are observed.

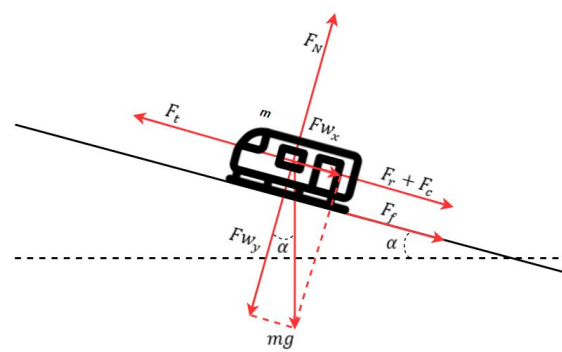


Figure 1. Free-body diagram of a locomotive.

The application of Newton's second law to the free-body diagram shown in Figure 1 is introduced in (1), where m represents the train mass, a is the acceleration, F_{tk} is the effort (tractive or braking) of the k th locomotive unit of the train, F_{rk} is the rolling resistance force of k th train element, F_c is the train curve resistance, and F_g is the train gradient force due to the slope of the track. Moreover, k represents the increment of mass due to rotating inertia, which varies from 0 to 0.3 depending on the type of vehicle and it may take values from 0.06 to 0.1 for a complete train. It is important to note that F_g can be positive if the train is ascending, or negative if the train is descending; moreover, u represents the number of locomotives and r the number of train elements (i.e., locomotive, coaches, etc.). The following paragraphs provide a brief description of the forces used in (1).

$$m(1+k) \cdot a(t) = \sum_{k=1}^u F_{tk}(t) - \sum_{k=1}^r F_{rk}(t) - F_c(t) - F_g(t) \quad (1)$$

The rolling resistance force represents the interaction of the train axles with the railway track and the wind effects on the locomotive at a given time. It is represented through Davis' Equation (2) [26], which is empirically determined considering three main coefficients. The first one is related to the type of locomotive and the type of railway track (A_k), which varies according to the track conditions, associating the resistance generated by the track, the friction between the rail and the wheel, and the effect of the weight on the track. The second and third coefficients (B_k and C_k) represent the effect of wind related to aerodynamic force and acceleration changes, which will have more impact at higher speeds.

$$F_{rk}(t) = A_k + B_k \cdot v(t) + C_k \cdot v(t)^2 \quad (2)$$

Moreover, the gravitational force is calculated according to (3) [21], where α is the track slope. This expression is related to the weight of the locomotive and the gradient it

experiences, which does not exceed 2% in most cases [21,27] due to the power limitations of the locomotives. Additionally, it is worth mentioning that this force may have positive or negative values depending on the inclination of the track.

$$F_g(t) = m \cdot g \cdot \sin(\alpha(t)) \quad (3)$$

Another force to be considered in the locomotive motion is the curvature-related force (F_c), which is produced when the wheels of the same axle are coupled and the locomotive is driving through a curve. In this case, there is a sliding effect on the wheel at the inner side of the curve, which generates additional friction that can be calculated with the empirical expression shown in (4) [28], where $2 \text{ m}^2/\text{s}^2$ is a factor attributed to the slippery effect and r_C is the curvature radius in meters.

$$F_c(t) = \frac{m \cdot 2}{r_C(t) - 55} \quad (4)$$

Additionally, the electrical load in passenger trains, in the case of diesel units, is provided directly by the locomotive, which involves a reduction of traction effort. This effect must be considered in the estimation of the tractive effort vs. the speed profile. In the case of electric units, these loads, so-called hotel loads, are supplied by the overhead lines.

Finally, it is important to mention that the analysis of the forces presented before corresponds to a particular point of the track at a given time instant. Hence, this analysis must be performed point-by-point in a given trajectory to estimate the locomotive power and energy consumption.

2.2. Calculation of Mechanical Power and Electric Energy Consumption

The calculation of the locomotive mechanical power (P) is determined through the product of the speed (v) and the total effort of the locomotives at each point of the specific trajectory, as shown in (6), where $\sum_{k=1}^u F_{tk}(t)$ can be calculated from (1) as shown in (5), where $F_{kt}(t)$ for a given speed is limited by the forces defined in the tractive and braking efforts profiles of each locomotive. It is worth noting that the total effort of the locomotives may take positive or negative values; hence, $P(t)$ can also be negative or positive if the locomotive is generating or consuming energy, respectively [29].

$$\sum_{k=1}^u F_{tk}(t) = m(1+k) \cdot a(t) + \sum_{k=1}^r F_{rk}(t) + F_c(t) + F_g(t) \quad (5)$$

$$P(t) = v(t) \cdot \sum_{k=1}^u F_{tk}(t) \quad (6)$$

After the estimation of $P(t)$, the total energy consumed by the locomotive at time t to move along the analyzed trajectory is calculated by integrating the positive values of $P(t)$ in a time window defined by the times t_0 and t , as shown in (7) [21]. It is important to highlight that $E(t)$ is the total mechanical energy provided by the locomotive; thus, the calculation of the electric energy consumed by the electric motors of the locomotive can be calculated with (8), where η_m is the efficiency of the locomotive's motors and their power converters.

Finally, the potential electric energy that can be generated with the locomotive at time t can be estimated as shown in (9), which corresponds to the integral of the negative values of $P(t)$ multiplied by two efficiencies and one factor. In (9), η_{gen} is the efficiency of the system that receives the energy generated by motors, and AF is the availability factor and represents the percentage of the locomotive braking mechanical power (i.e., $P(t):P(t) < 0 \text{ W}$) that can be used by the regenerative braking system, which may be between 20% and 30% [30]. For example, in a diesel locomotive with a battery bank, η_{gen} would be defined

as $\eta_{gen} = \eta_c \cdot \eta_b$, where η_c and η_b are the efficiencies of the power converters and the battery bank. Additionally, the typical efficiencies of the main locomotive technologies are illustrated in Table 1 [31,32].

$$E(t) = \int_{t_0}^t P(\tau) d\tau \quad \forall P(\tau) > 0 \text{ W} \quad (7)$$

$$E_d(t) = \frac{E(t)}{\eta_m} \quad (8)$$

$$E_g(t) = \eta_m \cdot \eta_{gen} \cdot AF \int_{t_0}^t P(\tau) d\tau \quad \forall P(\tau) < 0 \text{ W} \quad (9)$$

Table 1. Power conversion efficiencies of the main locomotive technologies [31,32].

Techology	Efficiency (η)
Diesel engine	37 a 41%
Main generator	90%
Power converters	95%
Traction motors	75 a 80%
Batteries	85%
Supercapacitors	95%

In summary, to estimate $E(t)$, $E_d(t)$, and $E_g(t)$, it is necessary to know the main characteristics of the locomotive and the railway track geometry to analyze the forces and determine $\sum_{k=1}^u F_{tk}(t)$ for each point along the track by using (5). With such information, it is possible to calculate $P(t)$ at each analyzed point of the track and to use (7)–(9) to estimate $E(t)$, $E_d(t)$, and $E_g(t)$, respectively.

3. Proposed Methodology

The flowchart in Figure 2 summarizes the proposed methodology to estimate the power and energy consumed by a locomotive on a given railway track. The process begins by defining the train to be analyzed to determine its main characteristics: tractive effort vs. speed profile, braking effort vs. speed profile, power conversion efficiency, total mass, rail gauge, Davis' equation constants (A_k , B_k , and C_k with $k = [1, \dots, r]$), nominal power, and maximum speed. It is worth noting that tractive and braking efforts profiles are usually provided as plots in the locomotives' datasheets; hence, those plots need to be digitized and interpolated to determine the tractive or braking force for a particular speed value.

Then, if the track information is complete, it has to be organized into the following vectors: time (\vec{t}), speed (\vec{v}), slope ($\vec{\alpha}$), and curvature radius (\vec{r}_C). Those vectors have n elements, where the i th element of each vector contains the information of the point of the track at time $t(i)$, where $t(1) = 0$ s. Otherwise, if the railway track information is not available, incomplete, or not reliable, then it is necessary to estimate the vectors described before, by tracing the railway track in a satellite imagery software tool such as Google Earth. The details to estimate \vec{t} , \vec{v} , $\vec{\alpha}$, and \vec{r}_C are described in the following subsections.

With complete information from the train and the railway track, it is possible to obtain the values of $\sum_{k=1}^r F_{rk}(t)$, $F_g(t)$, and $F_c(t)$ for each time by evaluating (2), (3), and (4), respectively, with $v(i)$, $\alpha(i)$, and $r_C(i)$ and the other input parameters. Then, the locomotives' force for each time ($\sum_{k=1}^u F_{tk}(t)$) is calculated by using (5). Later, combining this information with the train speed given in $v(i)$, it is possible to determine the mechanical power of the locomotives $P(t)$ at each time by using (6). Finally, the train power profile is obtained by plotting \vec{P} vs. \vec{t} and the total energy consumed is calculated by integrating the power profile according to (7), while the electrical energy and the potential energy generation can be calculated with (8) and (9), respectively.

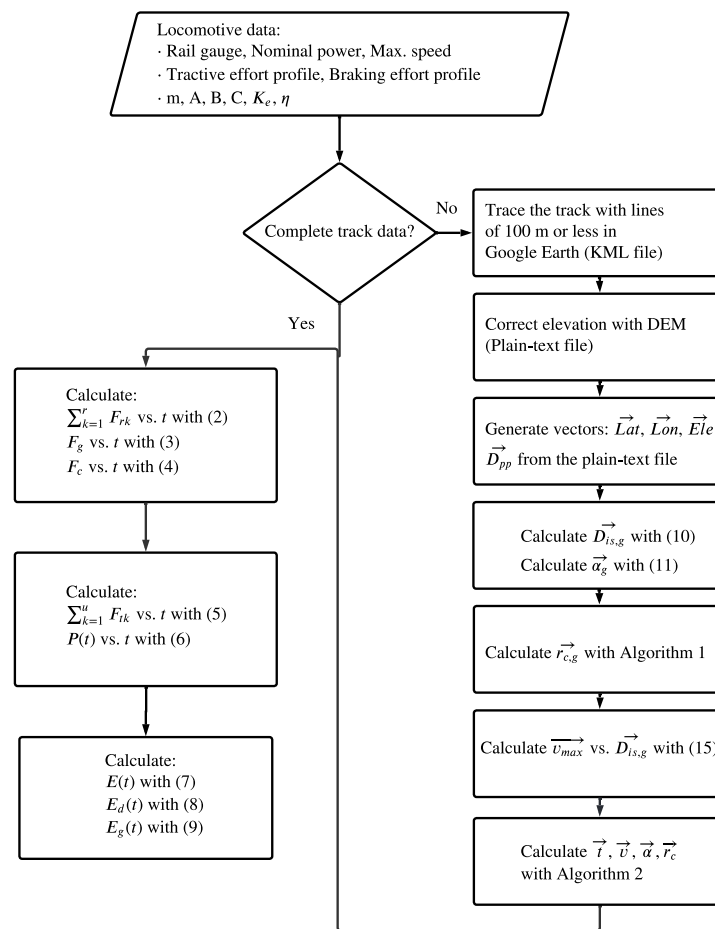


Figure 2. Flowchart of the proposed methodology.

The following subsections provide the details to extract the railway track data from satellite imagery as well as the calculation of the determination of the speed (\vec{v} vs. \vec{t}), slope (\vec{a} vs. \vec{t}), and curvature (\vec{r}_c vs. \vec{t}) time profiles.

3.1. Track Data from Satellite Imagery

The proposed methodology uses Google Earth to obtain the geographical coordinates of the railway track when there is no information or when the information is not complete or reliable. The first step is to trace the railway track using straight lines of 100 m, approximately. Then, the geographical data of each point in the track are exported in a KML file, which is based on the XML language, to provide not only the latitude, longitude, and elevation of each point but other data that can be useful for graphic information system mapping applications.

The elevation data from Google Earth may introduce significant errors in the elevation of each point. Therefore, one option to improve the elevation accuracy is to use the Digital Elevation Model database (DEM), which has a particular database for each region of the planet that best fits the elevation data. Those DEM databases can be accessed through the GPS Visualizer online tool [33], where the user can load a KML file and after a simple process obtain a plain-text file with the position data (i.e., latitude, longitude, and elevation) for each point of the railway track traced on Google Earth. In such a file, the information is organized in n_g rows, where n_g is the number of points used to approximate the track in Google Earth. Moreover, the columns include the point number, latitude (L_{at}), longitude (L_{on}), elevation (E_{le}), and distance between two consecutive points (D_{pp}).

At this point, the plain-text file has the main data required to calculate \vec{v} vs. \vec{t} , $\vec{\alpha}$ vs. \vec{t} , and r_C vs. \vec{t} profiles, which are required for the estimation of the forces acting on the locomotive.

3.2. Calculation of Elevation and Slope vs. Distance Profiles

The generation of the elevation vs. distance and slope profiles calculation begins by generating the vectors \vec{E}_{le} and \vec{D}_{pp} , which contain the n_g elevation and point-to-point distance data, respectively, obtained from the plain-text file described in Section 3.1. From \vec{D}_{pp} it is simple to calculate a vector with the distance of each point in the track ($D_{is,g}$) from the origin by applying (10), where $D_{is,g}(1) = 0$ m.

$$D_{is,g}(i) = D_{is}(i-1) + D_{pp}(i) \text{ for } i = [2, \dots, n-1] \quad (10)$$

The elevation vs. distance profile can be directly generated by plotting \vec{E}_{le} vs. $D_{is,g}$, while the vector with the slopes along the track is calculated from the \vec{E}_{le} and $\vec{D}_{is,g}$ vectors. The slope is calculated by assuming a straight line between two consecutive points regarding the elevation; therefore, the slopes are saved in a vector named $\vec{\alpha}_g$ where the last element is 0° and the rest of the elements are calculated as shown in (11). Then, the slope profile can be generated by plotting $\vec{\alpha}_g$ vs. $D_{is,g}$.

$$\alpha_g(i) = \tan^{-1} \left(\frac{E_{le}(i+1) - E_{le}(i)}{D_{is,g}(i+1) - D_{is,g}(i)} \right) \text{ for } i = [1, \dots, n-1] \quad (11)$$

3.3. Algorithm to Estimate the Curvature Radii vs. Distance Profile

The curvature estimation begins by generating the vectors \vec{L}_{at} and \vec{L}_{on} from the plain-text file described in Section 3.1. Those vectors have n_g elements that correspond to the n_g points traced along the railway track. Then, the curvature in the point $i+1$ is estimated by analyzing the coordinates of three consecutive points (i , $i+1$, and $i+2$ with $i = [1, \dots, n_g - 2]$) of \vec{L}_{at} and \vec{L}_{on} . Those points form a triangle, as shown in Figure 3; hence, there are $n_g - 2$ triangles along the track. Next, it is necessary to calculate the radius of the circle that passes through the three vertices of each triangle, or the radius of the circumcircle of each triangle, since such a radius represents the curvature radius at the point $i+1$ of the track. These concepts are illustrated in Figure 3.

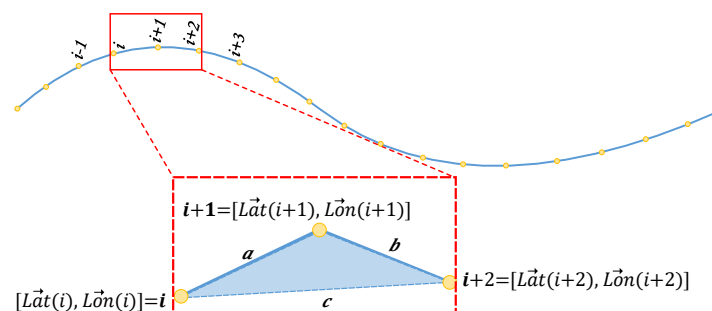


Figure 3. Concept illustration of the triangle formed by three consecutive points of the railway track used to find the curvature radius.

The curvature radius of the point $i+1$ (i.e., $r_{C,g}(i+1)$) is calculated by using (12), where A_t is the triangle area, while a , b , and c are the triangle sides between the points i and $i+1$, $i+1$ and $i+2$, and $i+2$ and i , respectively, (see Figure 3). In turn, a , b , and c can be calculated from the latitude and longitude of each point as shown in (13), where D is the distance between two coordinate points defined by their longitude and latitude, L_{at1} and L_{on1} are the coordinates of the first point, L_{at2} and L_{on2} are the coordinates of the second point, R is the earth radius, and x is defined in (14).

$$r_{C,g}(i+1) = \frac{(a \cdot b \cdot c)}{4 \cdot A_t} \quad (12)$$

$$D(L_{at1}, L_{on1}, L_{at2}, L_{on2}) = 2 \cdot R \cdot \arctan\left(\frac{\sqrt{x}}{\sqrt{1-x}}\right) \quad (13)$$

$$x = \left[\sin^2\left(\frac{L_{at2} - L_{at1}}{2}\right) + \cos(L_{at1}) \right] \cdot \cos(L_{at2}) \cdot \sin^2\left(\frac{L_{on2} - L_{on1}}{2}\right) \quad (14)$$

This procedure is repeated from $i = 1$ to $i = n_g - 2$ to estimate the curvature radius from point 2 to point $n_g - 1$ of the railway track, which are stored in a vector $\vec{r}_{C,g}$, where the first and last elements are defined as 0 m (i.e., $r_{C,g}(1) = r_{C,g}(n) = 0$ m). Then, the points with a curvature radius greater than $r_{C,th}$ are neglected (i.e., assumed 0 m) as shown in Figure 4, since $r_{C,th}$ is a threshold used to determine if a section of the track is considered as a curve or not. The next step is to analyze the resulting vector to find the groups of consecutive points in $\vec{r}_{C,g}$ with a radius less than $r_{C,th}$ and calculate the average of those radii ($r_{C,av}$). Finally, $r_{C,av}$ is assigned to the point of the group with the least curvature radius.

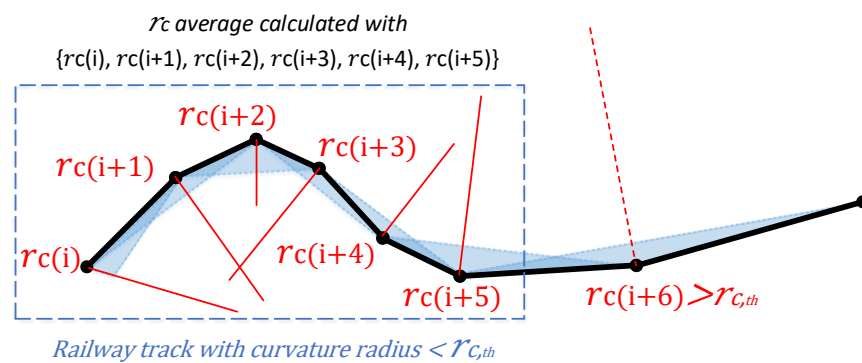


Figure 4. Concept illustration of the calculation of $r_{C,av}$ and its assignment to a point of a group of consecutive points with $r_C < r_{C,th}$.

Algorithm 1 summarizes the procedure to obtain $\vec{r}_C(i)$ with $i = [2, \dots, n_g]$. The first loop calculates the curvature radius for each point of the curve by using the procedure described before, while the second loop identifies the groups of consecutive curvature radii greater than 0 m and less than $r_{C,th}$ along with their average values and assigns this value to the element of the group with the minimum curvature radius.

Algorithm 1 Curvature radius ($r_{C,g}$) calculation

Inputs: $r_{C,th}$, \vec{L}_{at} , \vec{L}_{on}
Output: $r_{C,g}$

```

for  $i = 1$  to  $i = n_g - 2$  do
    Calculate  $a$  using (13) with  $L_{at1} = L_{at}(i)$ ,  $L_{on1} = L_{on}(i)$ ,  $L_{at2} = L_{at}(i + 1)$ ,
     $L_{on2} = L_{on}(i + 1)$ 
    Calculate  $b$  using (13) with  $L_{at1} = L_{at}(i + 1)$ ,  $L_{on1} = L_{on}(i + 1)$ ,  $L_{at2} = L_{at}(i + 2)$ ,
     $L_{on2} = L_{on}(i + 2)$ 
    Calculate  $c$  using (13) with  $L_{at1} = L_{at}(i + 2)$ ,  $L_{on1} = L_{on}(i + 2)$ ,  $L_{at2} = L_{at}(i)$ ,
     $L_{on2} = L_{on}(i)$ 
    Calculate  $A_t$  of the triangle
    Calculate  $r_{C,g}(i + 1)$  using (12)
    if  $r_{C,g}(i + 1) > r_{C,th}$  then
         $r_{C,g}(i + 1) = 0$  m
    end if
end for
 $r_{C,g}(1) = r_{C,g}(n) = 0$  m
 $r_{C,sum} = 0$  m,  $r_{C,min} = r_{C,th} + 1$ ,  $cnt = 0$ ,  $i_{min} = 0$ ,  $i_{fst} = 0$ 
for  $i = 2$  to  $i = n - 1$  do
    if  $r_{C,g}(i) \leq r_{C,th}$  &  $r_{C,g}$  then  $(i) > 0$  m
        if  $i_{fst} = 0$  then
             $i_{fst} = i$ 
        end if
         $r_{C,sum} = r_{C,sum} + r_{C,g}(i)$ 
         $cnt = cnt + 1$ 
        if  $r_{C,g}(i) < r_{C,min}$  then
             $r_{C,min} = r_{C,g}(i)$ 
             $i_{min} = i$ 
        end if
    end if
    if  $r_{C,g}(i + 1) > r_{C,th}$  then
         $r_{C,av} = r_{C,sum} / cnt$ 
         $r_{C,g}(i_{min}) = r_{C,av}$ 
        Set  $r_{C,g}(i) = 0$  m from  $i = i_{fst}$  to  $i = i_{fst} + cnt - 1$  excluding  $i = i_{min}$ 
        Reset auxiliary variables:
         $r_{C,sum} = 0$  m,  $r_{C,min} = r_{C,th} + 1$ ,  $cnt = 0$ ,  $i_{min} = 0$ ,  $i_{fst} = 0$ 
    end if
end for

```

3.4. Calculation of Speed, Elevation, Curvature, and Distance vs. Time Profiles

As mentioned in Section 2, it is necessary to know the speed, slope, and curvature radii vs. time profiles to calculate the forces acting on the train and the locomotive's power. In some cases, these profiles can be obtained from railway operators, who have experimental data from the daily movements of the trains as well as the track data. Nevertheless, in zones where speed data or itineraries do not exist or are not open to the public, it could be generated from existing international or national regulations.

The first step to define a speed profile is to calculate the maximum theoretical speed that can be achieved by the train at each point of the track to generate a maximum speed profile (i.e., v_{max} vs. $D_{is,g}$). Such a profile shows the restrictions for the speed profile generated from international and national regulations.

Each point of v_{max} can be calculated from (1) assuming that the acceleration is 0 m/s^2 , since the train moves at its maximum speed v_{max} , which results in (15). Additionally, in (15) the locomotive force F_{tk} is calculated from the tractive and braking efforts profiles provided by the manufacturer, which show the maximum force (tractive or braking) produced by a locomotive for a particular speed. Equation (15) corresponds to the time instant where

the train is at a particular point of the track, which means that F_c and F_g can be assumed constants while F_{tk} and F_{rk} are functions of v_{max} . Therefore, v_{max} for a point of the track is obtained by solving (15); then, the v_{max} vs. $D_{is,g}$ profile is calculated by repeating this process for the n_g points traced along the track.

$$\sum_{k=1}^u F_{tk}(v_{max}) - \sum_{k=1}^r F_{rk}(v_{max}) - F_c - F_g = 0 \quad (15)$$

The second step to determine a speed vs. time profile (\vec{v} vs. \vec{t}) is to define a speed vs. distance profile (\vec{v}_g vs. $D_{is,g}$) considering the national and international regulations and limited by the $k_v \cdot v_{max}$ vs. $D_{is,g}$ profile, where k_v is a value less than 1 to avoid defining an element of \vec{v} at its maximum theoretical value. Such a profile has n_g points and it is used along with $D_{is,g}$ to determine \vec{t} and, at the same time, the time profiles of the main variables: \vec{v} vs. \vec{t} , $\vec{\alpha}$ vs. \vec{t} , and \vec{r}_C vs. \vec{t} . It is important to mention that the subscript g in \vec{v}_g , $\vec{\alpha}_g$, and $\vec{r}_{C,g}$ represents the variable for each geographical point of the track given by $D_{is,g}$, while the variables without the subscript (i.e., \vec{v} , \vec{D}_{is} , $\vec{\alpha}$, and \vec{r}_C) contain the information for each time of the journey given by \vec{t} .

The calculation of the time profiles is described in Algorithm 2, where the inputs and outputs are defined and Δt , i_t , i_{vb} , i_{ve} , and i_{tb} are auxiliary variables. The first *If* is used to calculate Δt , which is the time required to move between two consecutive points of the track (i.e., $D_{is,g}(i)$ and $D_{is,g}(i-1)$) with the speed defined in the speed vs. distance profile ($v_g(i)$) when such a speed is greater than 0 m/s.

Algorithm 2 Calculation of \vec{t} , \vec{v} , $\vec{\alpha}$, and \vec{r}_C

Input: $D_{is,g}$, \vec{v}_g , $\vec{\alpha}_g$, $\vec{r}_{C,g}$, n_g , Δt_0

Output: \vec{t} , \vec{v} , $\vec{\alpha}$, \vec{r}_C

$\Delta t = 0$ s, $i_t = 1$, $i_{vb} = 1$, $i_{ve} = 1$, $i_{tb} = 1$

$t(1) = 0$ s, $v(1) = v_g(1)$, $\alpha(1) = \alpha_g(1)$, $r_C(1) = r_{C,g}(1)$

for $i = 2$ **to** $i = n_g$ **do**

if $v_g(i) > 0$ m/s **then**

$\Delta t = \frac{D_{is,g}(i) - D_{is,g}(i-1)}{v_g(i)}$

$i_t = i_t + 1$

$t(i_t) = t(i_t - 1) + \Delta t$, $v(i_t) = v_g(i)$, $\alpha(i_t) = \alpha_g(i)$, $r_C(i_t) = r_{C,g}(i)$

end if

if $v_g(i) = 0$ m/s **then**

$i_{ve} = i$

$\vec{v}_{aux} = v_g(i_{vb} : i_{ve} - 1)$, $t_{aux} = t(i_{tb} : \text{length}(\vec{v}_{aux}) - 1)$

$i_{vb} = i_{ve}$

 Calculate a_{aux} from \vec{v}_{aux} and t_{aux}

 Define A_{aux} as the numerical integration of a_{aux}

 Define a_n as the last element of a_{aux}

 Define Δt_n as the difference between the last two elements of t_{aux}

 Define v_n as the last element of \vec{v}_{aux}

 Calculate Δt with (16)

$i_t = i_t + 1$

$t(i_t) = t(i_t - 1) + \Delta t$, $v(i_t) = 0$ m/s, $\alpha(i_t) = \alpha_g(i)$, $r_C(i_t) = r_{C,g}(i)$

$t(i_t + 1) = t(i_t) + \Delta t_0$, $v(i_t + 1) = 0$ m/s, $\alpha(i_t + 1) = 0$ rad, $r_C(i_t + 1) = 0$ m

$i_t = i_t + 1$, $i_{tb} = i_t$

end if

end for

The second *If* has two objectives: the first one is to calculate Δt when $v_g(i) = 0$ m/s. The second objective is to determine Δt to guarantee that the train stops at each station of the route, which is defined as 0 m/s in \vec{v}_g . This condition can be met if the numerical

integration of the acceleration between two stops is 0 m/s. To achieve these two objectives the first step is to define \vec{v}_{aux} and \vec{t}_{aux} , which contain the elements of \vec{v}_g and \vec{t} between the last stop and the point before the actual stop, where the actual stop is identified if the condition $v_g(i) = 0$ m/s is true. Then, it is necessary to calculate the acceleration from \vec{v}_{aux} and \vec{t}_{aux} (i.e., a_{aux}) and numerically integrate a_{aux} to obtain A_{aux} . The variables described before are illustrated in Figure 5, which shows an example of normalized speed and acceleration profiles.

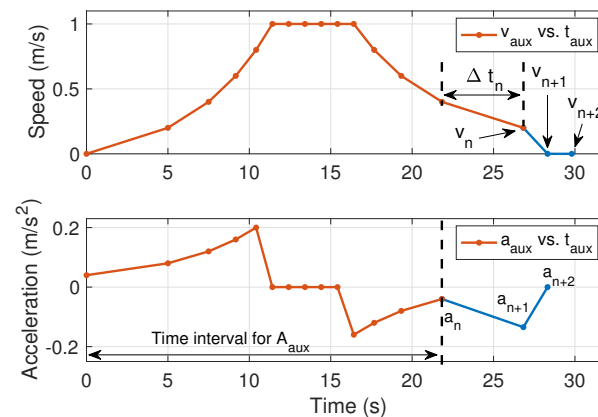


Figure 5. Concept illustration of the calculation of Δt when $v_g(i) = 0$ m/s to guarantee that the train stops.

The area under a_{aux} (A_{aux}) is positive; therefore, the area under the last three points of the acceleration profile (see Figure 5) must be $-A_{aux}$ to obtain a null integration of the acceleration profile. To simplify this analysis, it is possible to add a point of 0 m/s to \vec{v} (v_{n+2} in Figure 5) to obtain a point of 0 m/s² (a_{n+2} in Figure 5) in the acceleration profile. Then, equating the area under the points a_n , a_{n+1} , and a_{n+2} to $-A_{aux}$, it is possible to determine Δt as shown in (16).

$$\Delta t = \frac{\frac{-v_n \cdot \Delta t_n}{2}}{-A_{aux} + \frac{v_n}{2} - \frac{\Delta t_n \cdot a_n}{2}} \quad (16)$$

Considering that the procedure described above added an element to \vec{v} (v_{n+2} in Figure 5), it is also necessary to add an element to the other vectors (\vec{t} , \vec{a} , and \vec{r}_C). The element t_{n+2} is defined by adding Δt_0 to the previous time element of \vec{t} (t_{n+1} in Figure 5), where Δt_0 is a user-defined parameter. Moreover, the values of α and r_C for the time t_{n+2} are defined as 0 rad and 0 m, respectively, since the train is not moving (see the end of Algorithm 2).

At this point, all the vectors required to calculate the train's forces, power, and energy are available (\vec{t} , \vec{v} , \vec{a} , and \vec{r}_C) to perform the steps defined in the flowchart in Figure 2

4. Results and Discussion

The proposed methodology was applied to two case studies to validate the calculations of the forces, power, and energy, defined in Section 2, as well as the estimation of the track information from satellite imagery, as described in Section 3.

The first case corresponds to the route from Alcazar de San Juan to Cartagena in Spain, which is used in [21] to calculate the energy consumption of different locomotives. This case study is aimed at validating the calculations introduced in Section 2 by comparing the total energy consumption reported in [21] with the one obtained with the proposed methodology for a Vossloh diesel-electric locomotive reference S-334.

The second case corresponded to the route from Chiriguaná to Santa Marta in Colombia, which is one of the few railways routes used in this country. In this case study, there

was no available information on the route from the operators; hence, the proposed methodology was used to extract the route information from satellite imagery as described in Section 3. In this case, there was also no information about the locomotives and their loads; therefore, it was assumed that the same locomotive used in the first case study was moving on this route.

4.1. Case Study 1: Alcazar de San Juan to Cartagena–Spain

The first step in the methodology introduced in Figure 2 is to determine the main locomotive parameters. Some relevant parameters (such as nominal power, maximum speed, rail gauge, and weight) of the S-334 locomotive are introduced in Table 2, which are available in [34]. The methodology also requires the locomotive's tractive effort and braking effort vs. speed profiles, which are presented in [34] and are introduced in Figure 6. Those figures were digitized and interpolated, as explained in Section 3, to estimate the tractive or braking force for the estimation of the maximum theoretical speed.

The parameters used for the calculations were the following: $m = 208\text{ T}$, $k = 0.08$, $A_1 = 2540$, $B_1 = 33.44$ and $C_1 = 0.572$ (Davis constants for all the coaches), $A_2 = 1082$, $B_2 = 31.75$ and $C_2 = 3.82$ (Davis constants for the locomotive) [21], $\eta_m = 0.8$, $\eta_{gen} = 0.8$, $AF = 20\%$, and a hotel load of 15%.

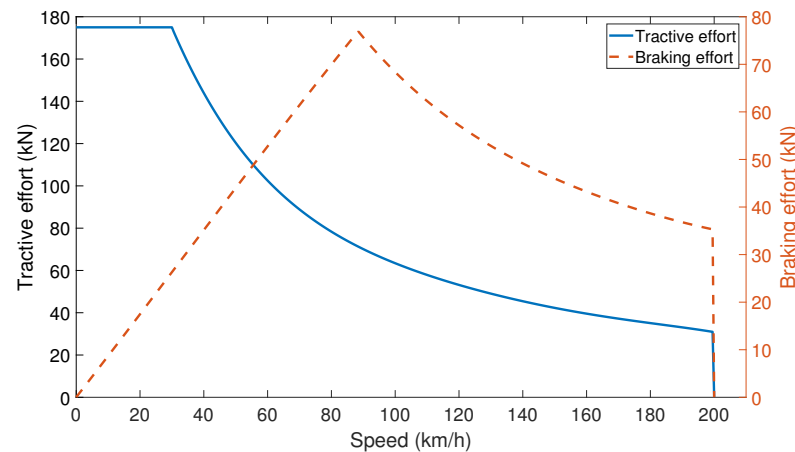


Figure 6. Tractive effort vs. speed profile.

Table 2. Vossloh S-334 diesel–electric locomotive characteristics.

Characteristic	Value
Manufacturer	Vossloh
Nominal power	3,256 CV
Maximum speed	200 km/h
Rail gauge	1435 mm, 1668 mm
Weight	90 ton
Engine	1 diesel 12N710G3B-EC
UIC type	Bo'Bo'
Year of manufacture	2006

In this case study, the railway track data were available in the plots reported in [21]; therefore, the elevation and speed profiles were obtained by digitizing the corresponding plots in [21]. Nevertheless, the detailed information on the curvature radii profile was difficult to obtain by digitizing the plot introduced in [21]; hence, the route from Alcazar de San Juan to Cartagena was traced in Google Earth with steps of 100 m, approximately, as shown in Figure 7. Applying the process introduced in Section 3.1, it was possible to obtain a plain-text file with 2216 points. Then, processing such file resulted in three vectors: $\vec{D}_{is,g}$, \vec{L}_{at} , and \vec{L}_{on} . Finally, the curvature radii profile could be calculated as explained

in Section 3.3, with $r_{C,th} = 500$ m [21], to obtain the vector \vec{r}_C and the profile shown in Figure 8.

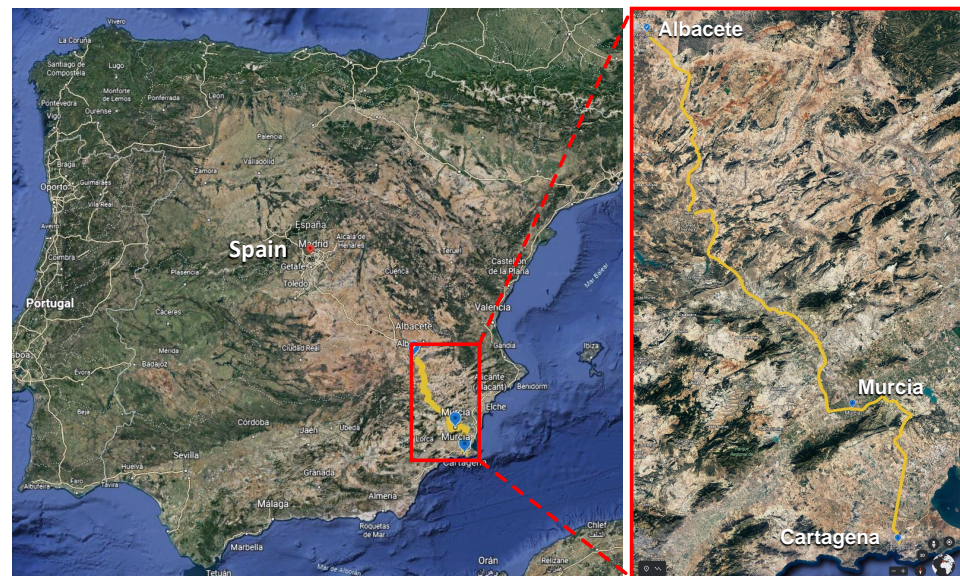


Figure 7. Albacete–Cartagena route traced in Google Earth.

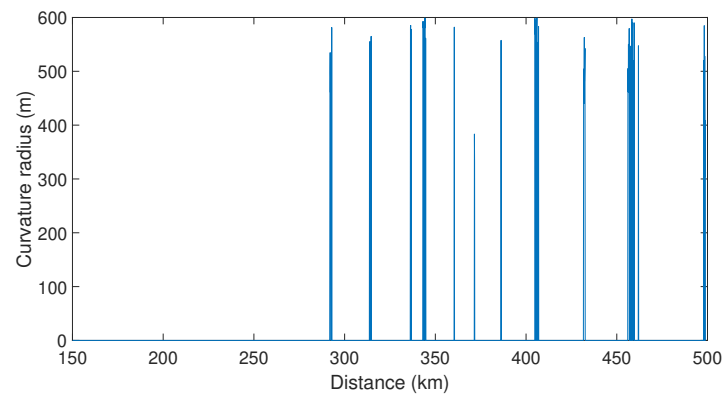


Figure 8. Curvature radius profile calculated with the proposed methodology with $r_{C,th} = 500$ m.

Afterward, the elevation vs. distance and speed vs. time profiles reported in [21] were digitized to obtain \vec{E}_{le} , $\vec{D}_{is,g}$, \vec{v} , and \vec{t} . This process resulted in the elevation and speed profiles reported in Figures 9 and 10, respectively. The railway track information was completed by generating the other vectors (\vec{D}_{is} , $\vec{\alpha}$, and \vec{r}_C) by using the procedure described in Section 3; however, the slope profile was not plotted because this information was contained in the elevation profile.

At this point, the locomotive and railway track information were available; hence, it was possible to calculate the forces at each point of the track as well as the power required by the locomotive to accelerate or decelerate the train. The plots shown in Figure 11a,b correspond to the powers provided in [21] and were estimated with the proposed methodology, respectively.

In those figures, it can be observed that the maximum values are similar (around 1.8 MW), but the minimum values differ (-2.5 MW for [21] and -2.2 MW for the proposed methodology). Moreover, in both cases, the power takes positive and negative values according to the positive and negative slopes in the tracks, where positive slopes require positive power and energy consumption, while negative slopes result in negative power and energy generation due to the regenerative braking systems. Comparing Figure 11a,b, there are also differences in the points where the power is positive and negative. The

differences described before are produced by unavoidable errors in the vectors \vec{D}_{is} , \vec{E}_{ele} , and \vec{a} induced by the digitization process. Those errors in \vec{a} cause α to be positive in [21] but negative in the digitized data in some points of the track, which produces a positive power in [21] but a negative power with the proposed procedure. Additionally, the digitization errors in the magnitudes of \vec{a} also produce differences in the magnitudes of \vec{P} , which affect the power profile and the energy estimation.

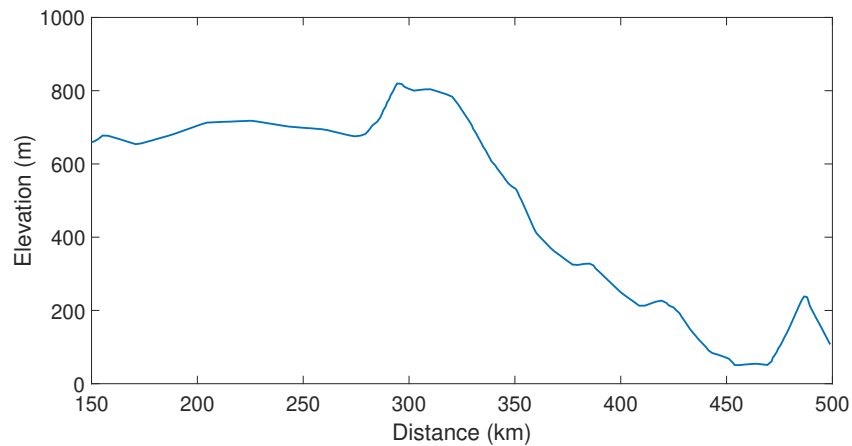


Figure 9. Elevation profile digitized from [21] under CC BY 4.0 license.

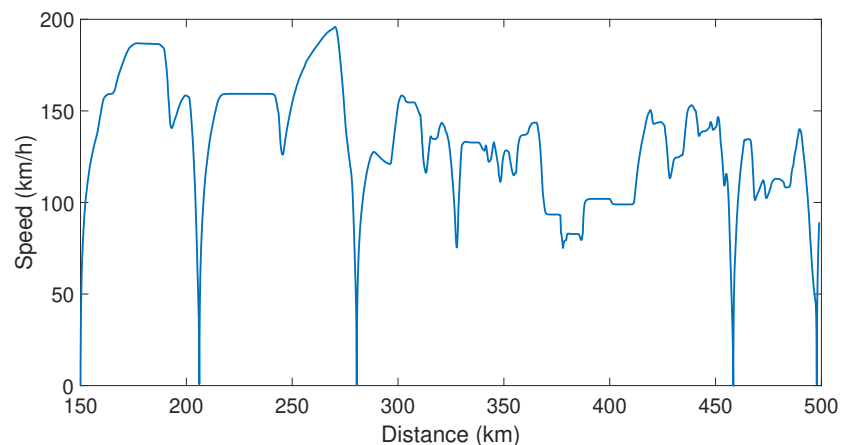


Figure 10. Speed profile digitized from [21] under CC BY 4.0 license.

However, calculating the locomotive mechanical power and the total energy consumption by using the proposed methodology, the estimated total electrical energy was $E_d = 2332.2$ kWh, which was close to the total electrical energy provided in [21] ($E_d = 2417.2$ kWh); therefore, the error in the energy consumption estimation was -3.5% . These values show that the calculations introduced in Section 2 and the methodology described in Section 3 agree with the results reported in [21]; hence, the proposed methodology can be used to estimate the power and energy consumption of a particular locomotive in a given route.

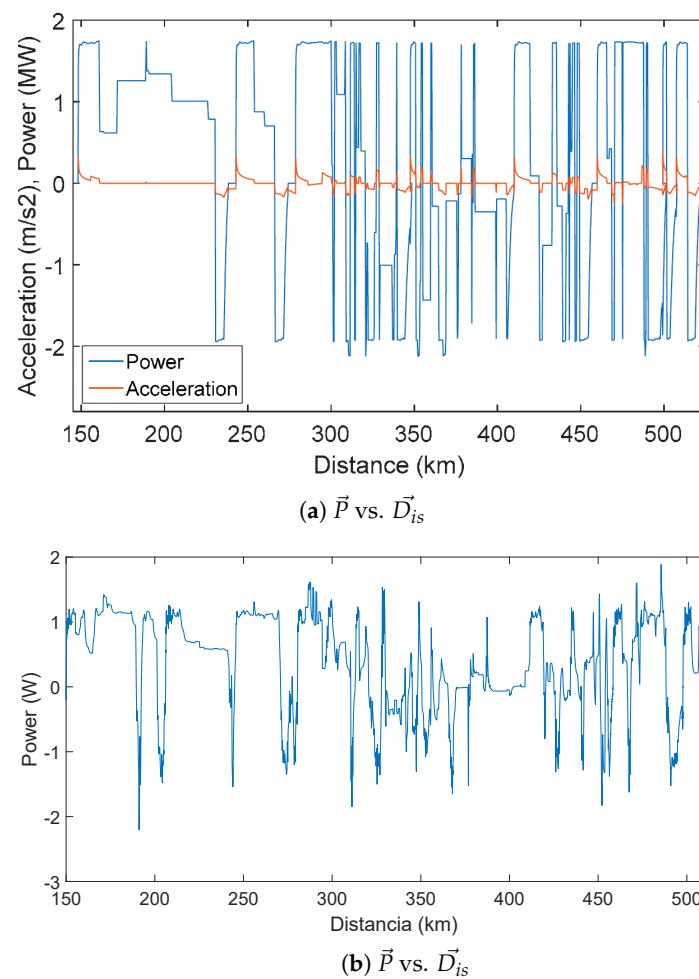


Figure 11. (a) Power vs. distance profile reprinted from [21] under CC BY 4.0 license and (b) Power vs. distance profile obtained with the proposed methodology.

4.2. Case Study 2: Chiriguaná–Santa Marta—Colombia

For this case study, it is important to mention that the route is not electrified; therefore, only diesel–electric locomotives must be considered. Following the methodology proposed in Section 3, the first step was to determine the main locomotive information. However, for this case study, it was assumed that the same model as in case study one (i.e., Vossloh S-334) was used; hence, the same parameters introduced in Section 4.1 were adopted including $k_v = 0.775$ and $\Delta t_0 = 4.5$ s for the generation of the speed vs. time profile. In addition, the use of a diesel–electric locomotive S-594-2 was included in order to compare the energy performance of two locomotives on the same track. The main characteristics of the S-594-2 locomotive are related in Table 3 and its tractive and braking effort curves are illustrated in Figure 12.

The parameters used for the calculations of the S-594-2 locomotive were the following: $m = 231$ T, $k = 0.08$, $A_1 = 2540$, $B_1 = 33.44$ and $C_1 = 0.572$ (Davis constants for all the coaches), $A_2 = 1229$, $B_2 = 39.86$ and $C_2 = 3.82$ (Davis constants for the locomotive) [21], $\eta_m = 0.8$, $\eta_{gen} = 0.8$, $AF = 20\%$, $k_v = 0.775$, $\Delta t_0 = 4.5$ s, and a hotel load of 15%.

As mentioned before, the railway track information for the route Chiriguaná–Santa Marta from Figure 13 was not available; as consequence, the first step was to trace the route with lines of 100 m approximately, using Google Earth, to obtain a KML file with the information of 2461 points. Then, the data were processed using GPS Visualizer to obtain a plain-text file with the information of elevation (from DEM using SRTM3 database NASA [35]), latitude, longitude, and distance between the consecutive points. From such a file, it was possible to generate the vectors \vec{E}_{le} , \vec{D}_{pp} , \vec{L}_{at} , and \vec{L}_{on} .

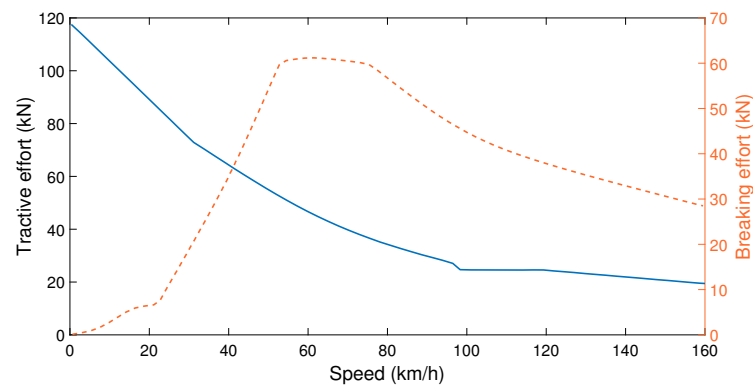


Figure 12. Tractive vs. speed profiles.

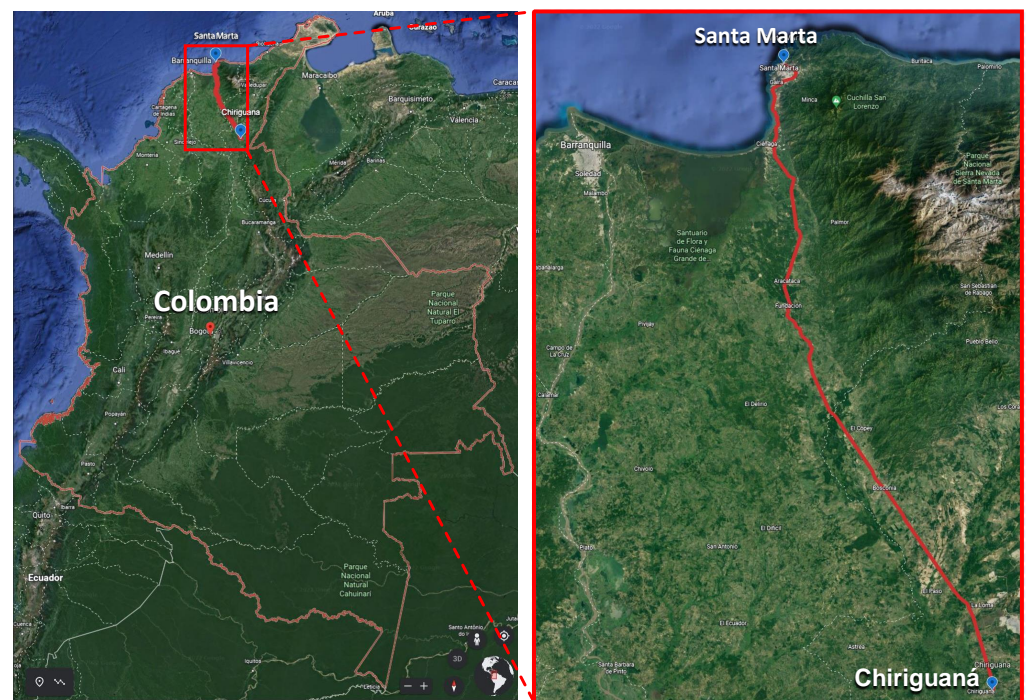


Figure 13. Map of the railway track Chiriguana–Santa Marta.

Table 3. CAF S-594-2 diesel–electric locomotive characteristics.

Characteristic	Value
Manufacturer	CAF
Nominal power	1609 CV
Maximum speed	160 km/h
Rail gauge	1435 mm, 1668 mm
Weight	130 ton
Engine	4 diesel MAND866 LUE206
UIC type	Bo Bo
Year of manufacture	2001

The vectors with the distances from the origin ($\vec{D}_{is,g}$) and curvatures ($\vec{r}_{C,g}$) were calculated as explained in Sections 3.2 and 3.3 (with $r_{C,th} = 800$ m), respectively. Nonetheless, the elevation had many changes in its values due to the estimation process performed from the DEM database. Those changes may suggest that the locomotive experiences changes in the slope sign every 100 m, which is not realistic and introduces errors in the estimation of the locomotive power. Therefore, the elevation profile (i.e., \vec{E}_{le} vs. $\vec{D}_{is,g}$) was smoothed

by using a moving average filter with five samples. The original and filtered elevation profiles are introduced in Figure 14, where it can be observed that the filtered profile shows a significant reduction in the number of changes in the elevation regarding the distance.

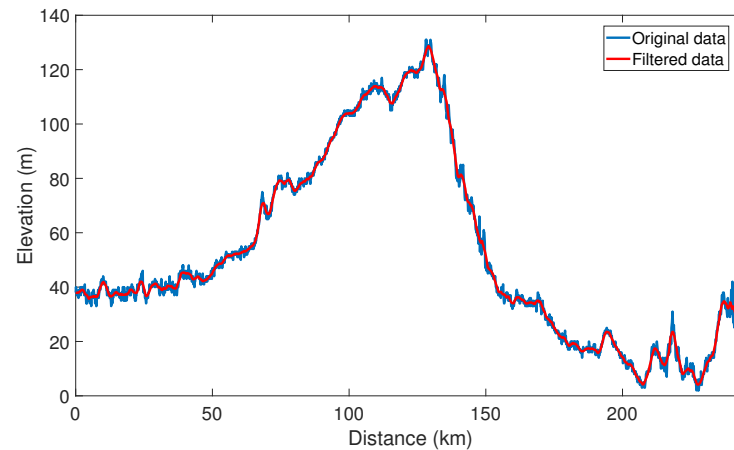


Figure 14. Original and filtered elevation profiles of the route Chiriguaná–Santa Marta.

Now, the curvature radii vs. distance profile was calculated by using Algorithm 1, which produced the vector $r_{C,g}$. The location and radii of the curves along the route are presented in Figure 15. This figure was obtained by plotting $r_{C,g}$ against $D_{is,g}$. In this case, 32 curves were identified with $r_{C,th} = 800$ m, where the minimum curvature radius was 255 m.

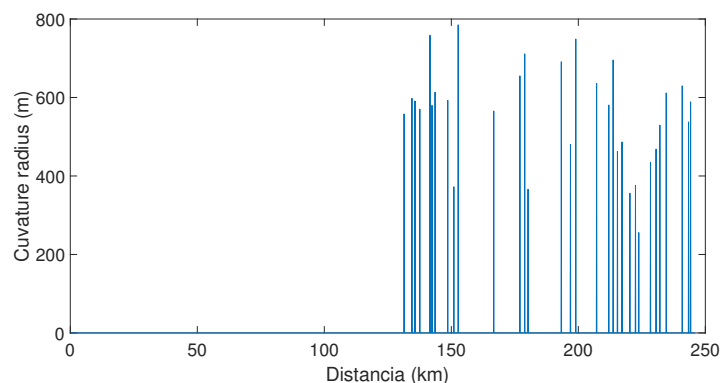


Figure 15. Location of curves and their radii of the route Chiriguaná–Santa Marta.

Given the lack of information on speed profiles in the analyzed route, the proposed speed vs. distance profile (\vec{v}_g vs. $D_{is,g}$) assumed that the locomotive moved at the maximum speed allowed by the Colombian rail traffic regulation [36]. This regulation defines a maximum speed of 50 km/h in residential zones and 80 km/h in open zones. Additionally, the speed profile also considered two theoretical stations in two towns (Bosconia and Fundación), where the speed goes down to 0 km/h. Those stations are located at 87 km (Bosconia) and 157 km (Fundación) from the Chiriguaná station. The maximum speed profile (\vec{v}_{max} vs. \vec{D}_{is}) was also calculated as described in Section 3.4 to determine the speed restrictions. For the train with the S-334 locomotive, \vec{v}_{max} was greater than the maximum speeds defined by the Colombian regulation at all the points of the track; however, this was not the case for the same train with the S-594-2 locomotive. The \vec{v}_g vs. $D_{is,g}$ and \vec{v}_{max} vs. $D_{is,g}$ profiles used for this case study are reported in Figures 16 and 17 for the S-334 and S-594-2 locomotives, respectively. It is worth noting that $k_v = 0.775$ is considered to limit the \vec{v} vs. \vec{t} for S-334 and S-594-2 locomotives; hence, the speed profile presented in Figure 16 is not affected by \vec{v}_{max} , while the one presented in Figure 17 is defined by $k_v \cdot \vec{v}_{max}$ for most of the route.

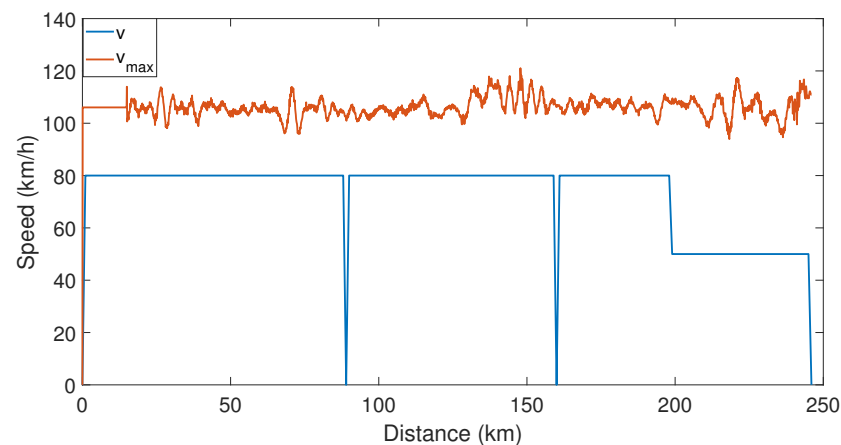


Figure 16. Speed profile of the route Chiriguana–Santa Marta with S-334 locomotive.

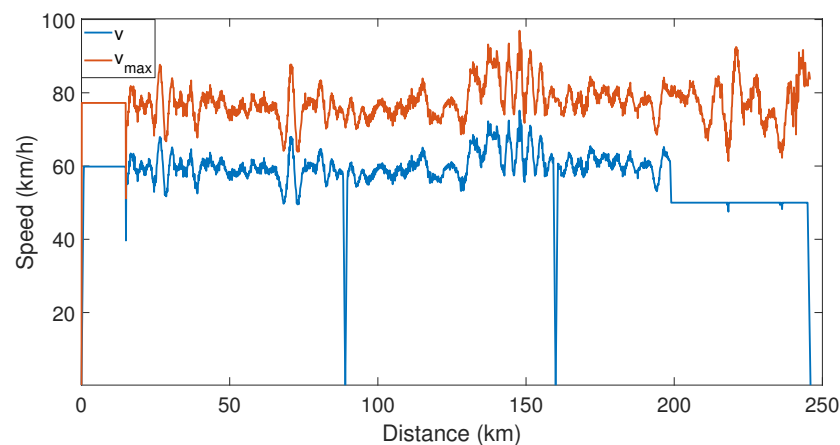


Figure 17. Speed profile of the route Chiriguana–Santa Marta with S-594-2 locomotive.

Using Algorithm 2 resulted in \vec{t} , \vec{v} , \vec{D}_{is} , \vec{a} , and \vec{r}_C ; hence, at this point, it was possible to calculate the mechanical power of the train at each point of the route (\vec{P}) by using (6). The estimated power profile was obtained by combining \vec{P} and \vec{v} , as shown in Figure 18, which was used to calculate the total energy consumed by the locomotive according to (7). Moreover, during the deceleration and in negative slopes, the mechanical power is negative, and such power represents the theoretical energy that could be generated, which was computed using (9). Finally, the electrical energy demand was computed from (8), which represents the energy needed by traction motors to move along the studied path. Those values are compiled in Table 4 for the two studied locomotives, as well as the time required to complete the route.

Figure 18 also shows that the maximum and minimum values of the mechanical power for the S-334 locomotive are 1.73 MW and -1.43 MW, respectively; and for the S-594-2 locomotive the maximum and minimum values are 0.77 MW and -1.01 MW, respectively, which is in agreement with the mechanical power that diesel motors can deliver to each locomotive. Moreover, for the S-334 locomotive, it can be observed that the required power peaks are experienced at the moments of braking and starting. On the other hand, it is possible to observe that in most parts of the route there is a positive consumption for the S-334 locomotive, so the potential generated energy is less than that of the S-594-2 locomotive. In the case of the S-594-2 locomotive, it can be observed that the power changes between negative and positive values due to the variations of the speed profile (see Figure 17).

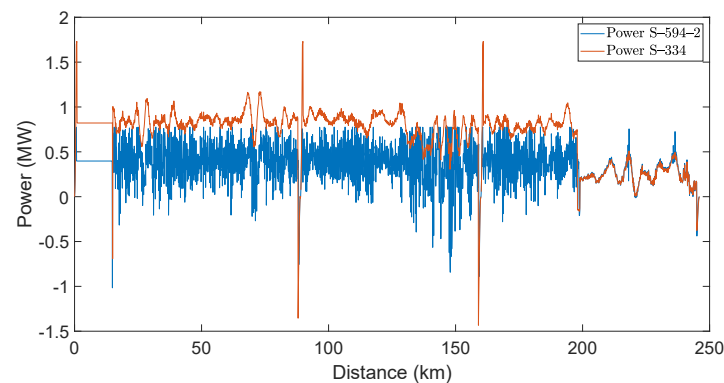


Figure 18. Power vs. distance profile, Chiriguaná–Santa Marta route.

Table 4. Simulation results for the studied locomotives.

Locomotive	E (kWh)	E_d (kWh)	E_g (kWh)	Time (h)
S-334	2247.8	3231.2	5.2811	3.60
S-594-2	1558.6	2240.1	7.7202	4.42

These results show that both locomotives can move the train along the route with some differences. On the one hand, the S-334 locomotive can reach the maximum speed defined by the Colombian regulations and complete the route in 3.60 h, which requires an electrical energy consumption of 3231.2 kWh and has a potential to generate 5.2811 kWh. On the other hand, the maximum power of the S-594-2 locomotive does not allow reaching the maximum speed defined by the Colombian regulations; as consequence, regarding the S-334 locomotive, the time to complete the route is longer (4.42 h), but the electrical energy required is smaller (2240.1 kWh) and the potential energy generation bigger (7.7202 kWh).

The results of the case studies presented in this section show the applicability of the proposed methodology to estimate the power and energy consumed by a locomotive when the track information is not complete or not available. Therefore, the proposed methodology can be used for different applications, such as assessing the energy consumption (E) of different locomotives for a given route to select the best option; or estimating the power consumed by the locomotive at each point of the route as well as the potential energy that can be generated (E_g), to inject into the grid or to be used in energy storage systems.

5. Conclusions

A methodology for estimating the energy consumption and the potential energy generation of a locomotive, when the railway track information is not available or incomplete, was presented in this paper. The methodology started by extracting the main technical information of the locomotive to be analyzed. Then, the railroad track was traced in Google Earth with 100 m steps, from which longitude, latitude, and elevation data were extracted to estimate the track's slope and curvature profiles. Moreover, the methodology proposed to create a speed profile based on the data provided by the track operator or the regulations of the country where the analysis is to be implemented, but considering the maximum theoretical speed at each point of the track. The estimation of the locomotive power at each point of the route was generated with the collected information to finally calculate the energy consumed. Hence, the proposed methodology can help railway companies determine the best locomotive for a given route during the period of planning, construction, and operation, which may positively affect the economic, environmental, and other indicators of a railway project.

This methodology was initially tested on a Spanish railway route, for which the data published by other authors were available. Likewise, the results were compared between a model with sufficient information and the proposed methodology to estimate the energy

consumption of a train, presenting an error of 3.5% between both data. This error was attributed to the digitization of the information taken from the case in Spain. Finally, the methodology was applied to one of the Colombian railroads, the results providing sufficient information to determine the energy to be provided in the proposed trajectory for a possible upgrade of the locomotive technology and planning of the railway infrastructure and energy generation systems. Two different diesel–electric locomotives were compared for the case study in Colombia. Such a comparison showed that the locomotive power limited the maximum speed that could be reached by a train on the studied route, which translated into longer traveling times for the same load. Moreover, the energy consumed and generated by the two locomotives was significantly different, which showed that the proposed methodology could be used to evaluate different technologies for a particular application.

In future work, we propose to extend the data collection to other rail trajectories without public information and to identify tracks in a country where such information is not available. In this way, it will be possible to estimate the energy consumption and propose technological upgrades to improve freight and passenger transportation in a region. Moreover, it would also be interesting to use the proposed procedure for optimization problems such as the reduction of emissions, the reduction of fuel consumption, or the reduction of the charging/discharging cycles of energy storage systems.

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