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ENERGY SAVING AND DISTANCE TRAVELED OF THE RAILWAY TRAIN FROM ITS BIRTH TO THE FOURTH INDUSTRIAL REVOLUTION MODELING

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Abstract

The simulation of railway systems plays a key role in the design of the supply of the railway network but also in the functionality of the train itself. Various studies have been carried out to understand the railway network and by extension the operation of the trains. [1,2] The history of the railway is an everlasting history of speed. The rail mode is a guided and low grip transit mechanism. Since the beginning of the Industrial Revolution at the start of the 19th century, when rail first emerged in Europe, passenger train speed has been crucial for competition—not necessarily with other kinds of transportation, but with other rail firms. Additionally, it gave verifiable proof of technological advancement in the time's most developed nations. In this work, an approach is studied for the modeling and simulation using Anylogic PLE regarding saving the energy and the distance traveled for five distinct time periods.

Key Words - train, railways, industrial period and simulation

1. Introduction

The purpose of this study is to simulate the movement of the train from its birth until today when we are going through the fourth industrial revolution and we are at the beginning of the fifth. In order to achieve this, typical examples of trains per industrial time period are used. Using the Anylogic PLE simulation software, the energy savings achieved per time period and also the distance traveled over time are examined. Finally, all the elements of the hypotheses in question are compared and contrasted in a common diagram.

The first workable steam locomotive was launched by Englishman Richard Trevithick in 1804, averaging less than 10 mph. [1,3]

Fig. 1 Richard Trevithick's steam locomotive | Museum Wales [3]

1.1 Before the Industrial Revolution

An Englishman named Sir Goldsworthy Gurney (1793-1875), who built steam-powered carriages more than 50 years before gasoline automobiles were invented. With breaks for water and fuel, the Gurney Steam Carriage Company traveled the London to Bath route in 1829 at an average pace of 14 miles per hour, which is nearly twice as fast as a horse-drawn coach.

Fig. 2 With top speeds of 20 mph, Gurney Steamers operated excursions to Edgeware, Barnet, and Stanmore. [4]

1.2 First Industrial Revolution

The two most important components in the railway – the track and the locomotive – were developed during the industrial revolution (1750-1840). George Stephenson built the first railway in the world in 1825 to connect the English cities of Stockton and Darlington. Coal was to be transported along the railway. Steam engines were used to pull the carts. Horse-drawn carriages were used to transport passengers.

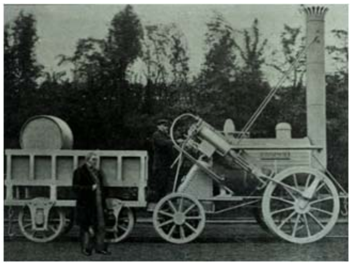

Fig. 3 George Stephenson and the Rocket locomotive [5]

1.3 Second Industrial Revolution

The combination of the steam engine and the rail at the beginning of the 19th century contributed tremendously to man's possibilities of high-speed travel. 6.5 km/h for stagecoaches in 1840 compared to a commercial speed of roughly 60 km/h for railroads as early as 1854.

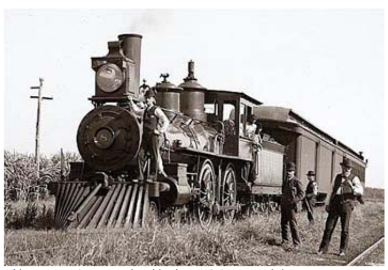

Fig. 4 Sierra Railway #3 was built in 1891 and has a top speed of about 50 MPH [6]

1.4 Third or Digital Industrial Revolution

In 1973, the prototype HST British Rail Class 41 recorded a top speed of 143 mph (230 km/h) in a test run the line. British legislation required the use of in-cab signaling for running at speeds more than 125 mph (201 km/h) and so regular trains services were unable to run at such speeds. The lack of in-cab signaling was the primary reason that prevented the InterCity 225 trainsets from operating at their design speed of 140 mph (225 km/h) during normal service. A secondary factor was that the signaling technology of the time was insufficient to allow detection of two broken rails on the running line. [7-9]

Fig. 5 British Rail Class 41 (HST) [10]

1.5 Fourth Industrial Revolution

The TGV (Train à Grande Vitesse) of France now holds the record for the fastest conventional wheeled passenger train, having attained 574.8 km/h (357.2 mph) over a 140 km (87 mi) section of track in 2007. [11]

Fig. 6 The French intercity high speed train called TGV (Train à Grande Vitesse). This specific engine set the world record for the fastest wheeled train on the 3rd of April 2007. It reached an amazing speed of 574.8 km/h. [12]

2. Description of Hypothesis and Simulation Process

Table 1. Description of Energies affecting positive the system [4]

Value	Description of the Energies
Einv	This is the energy from the inverter.
Erec	This is the rectifier's energy. Substation losses can be produced by the use of rectifiers and inverters with electricity (Esl). In this study, it is assumed that the rectifier power efficiency (_rec) and inverter power efficiency (inv), which have values of 97% and 95%, respectively, are constants.
Ereg	The energy that can be used for regenerative braking is called Ereg, while the energy that the brake rheostat expels is called Eeb_r. The auxiliary system or the catenary system can directly recycle and reuse some of the energy consumed by the electro-braking system. However, excessive regeneration may result in an increase in train voltage. The excess electro-braking energy is absorbed by the braking rheostat in order to shield the train from overvoltage.
Emr	This energy is the required amount to overcome motion resistance.
Erec	This is the rectifier’s energy.
Einv	This is the inverter’s energy.
Ekin	This is the kinetic energy of the system.

Table 2. Description of Energies affecting negative the system [4]

Value	Description of the Energies
Erub	This is the Friction Energy.

Es	The railway receives its power from the AC electricity grid. After the traction substation energy has been corrected from the AC network, the excess regenerative braking energy can be reversed back into the AC network. This is the energy that was consumed.
Esl	To power moving trains, the DC catenary system receives electricity from substations. Transmission loss (Etl), which is caused by the current flowing through conductor rails, is dependent on both the resistance of the conductor rail (reconductor) and the amount of current flowing through it. This is the energy from the substation losses.
Etl	Moving trains are supplied with electricity by a DC catenary system that receives it from substations. Transmission loss (Etl), which is caused by the current flowing through conductor rails, is dependent on both the current and the resistance of the conductor rail (reconductor). This is the energy from the transmission losses.
Etr_r Etr_e	The traction and auxiliary system use the train energy (Etr) from the DC catenary system. Onboard converters and motion resistance help to disperse some of the traction energy. The train gains kinetic energy, which is subsequently released by the braking mechanisms. This is the energy train που διαχωρίζεται σε regenerative και efficiency.
Ecl	This is the energy from the conversion losses.
Eeb	This is the energy from the electro-braking system.
Eaux	This is the energy from the auxiliary system.
Eeb_r	This is the energy that the brake rheostat has lost.

3. Methodology

The grid of AC electricity supplies the railway with energy. After the traction substation energy has been corrected from the AC network, the excess regenerative braking energy can be reversed back into the AC network. Equation as below, where Erec is the energy from the rectifier and Einv is the energy from the inverter, can therefore be used to compute the overall system energy consumption (Es). [4]

$$E_s = E_{rec} - E_{inv}$$

Substation losses can be produced by the use of rectifiers and inverters with electricity (Esl). In this study, it is assumed that the rectifier power efficiency (_rec) and inverter power efficiency (_inv), which have values of 97% and 95%, respectively, are constants. As a result, Equation can be used to compute the substation losses. [13,1]

$$E_{sl} = E_{rec} \times (1 - \eta_{rec}) + E_{inv} \times (1 - \eta_{inv})$$

To power moving trains, the DC catenary system receives electricity from substations. Transmission loss (Etl), which is calculated by the resistance of the conductor rail (reconductor) and the current flowing through it using Equation, is produced by the current through conductor rails. [14,1]

$$E_{tl} = \int r_{conductor} \times i^2 dt$$

The train energy (Etr) from the DC catenary system is used by the traction and auxiliary systems. Some of the traction energy is dispersed with the use of motion resistance and onboard converters. The train builds up kinetic energy, which the braking systems then release. The energy of the train can be stated in the form [15,1], where Ecl denotes conversion loss, Emr the energy needed to overcome motion resistance, Eeb the energy for the electro-braking system, and Eaux the energy for the auxiliary system.

$$E_{tr} = E_{cl} + E_{mr} + E_{eb} + E_{aux}$$

The auxiliary system or the catenary system can directly recycle and reuse some of the energy consumed by the electro-braking system. However, an excessive amount of regeneration can raise the train voltage. The excess electro-braking energy is absorbed by the braking rheostat in order to shield the train from overvoltage. Equation [16,1], where Ereg is the usable regenerative braking energy and Eeb r is the energy lost by the braking rheostat, defines the regeneration efficiency (_reg), which is used to assess the efficiency of regenerative braking energy.

$$\eta_{reg} = \frac{E_{reg}}{E_{eb}} = \frac{E_{reg}}{E_{eb\_r} + E_{reg}}$$

The total energy used by the entire system is equal to the sum of the energy lost during transmission, substation, and train operations, less regenerative braking energy. Thus, the energy flow from the level of the railway system should be in accordance with the energy conservation equation depicted in [17,1]. Complex interactions exist between the system energy flows. An extensive analysis of the infrastructural variables and operation controls is often required to estimate the energy flow characteristics of a feasible railway line.

$$E_{rec} - E_{inv} = E_{sl} + E_{tl} + E_{tr} - E_{reg}$$

4. Methods and Energy consumption

Based on the assumptions and results of [1], for a case study that the speed restriction along stations is restricted to 40km/h and are included in the following table, a different scenario is examined.

The research in question will focus on the calculation of the power (energy) that a commercial train has per season. The division of the eras will be made according to the periods of the industrial revolution. Consequently, and taking into account the aforementioned the present research was carried out in order to investigate the difference and the evolution of the train of these time periods. As data regarding the speed of each train, the data obtained from research on the web and in particular the maximum value thereof (as recorded) were used. Below are the speeds after conversion to km/h.

Table 3. Maximum speed records per time period

Time period	Mph	Km/h
Before industrial revolution	16	22.5308
1st industrial revolution	20	32.1869
2nd industrial revolution	37.2823	60
3rd industrial revolution	140	225.308
4th industrial revolution	357	574.8

Table 4. Energy consumption of the 40 km/h case study.

Scenario Index	1	2	3	4	5	6	7	8	9	10
Auxiliary Power (kW)	0	0	0	0	0	480	480	480	480	480
Headway (s)	90	100	120	300	600	90	100	120	300	600
E_s (kWh)	802	796	825	840	845	2221	2221	2214	2199	2191
E_{rec} (kWh)	816	803	859	957	1066	2221	2221	2215	2209	2224
E_{inv} (kWh)	−14	−8	−34	−117	−222	0	0	0	−10	−34
E_{sl} (kWh)	25	24	28	35	44	67	67	66	67	69
E_{fl} (kWh)	16	13	17	12	10	84	73	67	33	21
E_{tl} (kWh)	48	46	65	74	74	74	72	81	72	74
E_{tr_demand} (kWh)	1507	1507	1507	1507	1507	1507	1507	1507	1507	1507
E_{tr} (kWh)	1507	1507	1506	1507	1507	1476	1489	1479	1507	1507
E_{eb} (kWh)	796	796	796	796	796	796	796	796	796	796
E_{reg} (kWh)	794	795	791	788	790	796	796	796	796	796
E_{aux} (kWh)	0	0	0	0	0	1316	1316	1316	1316	1316
η_{reg}	100%	100%	99%	99%	99%	100%	100%	100%	100%	100%
Time of under-voltage (s)	0	0	8	0	0	312	192	250	3	0
Time of train running (s)	9900	9900	9900	9900	9900	9900	9900	9900	9900	9900

Table 5. Energy consumption of the 40 km/h case study.

Parameters	Value/Equation
Train mass with passengers, tonnes	301
Train formation	3M3T
Train length, m	148
Rotary allowance	0.08
Train Resistance, N/tonne	$3.49 + 0.039\,v + 0.00066\,v^2$ (v: km/h)
Maximum traction and braking power, kW	2518
Maximum operation speed, km/h	80
Maximum traction effort, kN	351

The parameters used for the calculations are as follows [18]:

Table 6. Energy consumption of the 40 km/h case study.

Name	Type – Value	Explanation
g	9.81	Acceleration of gravity in m/s^2
m	301000	Measurement in kg
μ_k	0.57	Sliding friction constant
μ_s	0.75	Constant of static friction
v0	22.5308	Train speed in IIoT
v1	32.1869	Train speed in IioT1
v2	60	Train speed in IioT2
v3	225.308	Train speed in IioT3
v4	574.8	Train speed in IioT4

The values of the forces acting on the system and by extension the total energy produced are shown in the following table. The values already assigned to some of the actions below derive from the average of the ten scenarios in Table 4:

Table 7. Explanation of Energies affecting the system

Name	Type – Value	Explanation
Erub	μ_k*m*g	Energy produced by the force of sliding friction
Etr_e	1507	Energy produced by the train (divided
Etr_r	1499.2	into regenerative and efficiency)
Esl	49.2	Energy produced by the electricity generated from substations
Erec	1559.1	Energy produced from the electricity generated through rectifiers and inverters that can generate substation losses
Es	1515.4	Energy produced from the traction substation
Etl	68	Energy produced because of the current that goes through conductor rails and generates transmission loss, which is determined by the resistance of the conductor rail
Ereg	793.8	Energy produced by the useable regenerative braking
Einv	-411	Energy produced from the inverter

Since the actions developed until the end of the movement are differentiated by means of movement and are divided into three distinct movements (beginning of movement, intermediate movement, end of movement). More specifically:

Table 8. Description of the forces and flows at the beginning of the process

Name	Type - Value	Explanation
Ein	Ereg	Equals to the initial energy of the system (same for all trains examined)
IIoT	E_{IIoT}	Equals to initial energy given E_{in}
IIoT1	E_{IIoT1}	Equals to initial energy given E_{in}
IIoT2	E_{IIoT2}	Equals to initial energy given E_{in}
IIoT3	E_{IIoT3}	Equals to initial energy given E_{in}
IIoT4	E_{IIoT4}	Equals to initial energy given E_{in}
E_{kin}	$m*V_0*V_0*1/2$	The kinetic energy of the train at state 0
E_{kin1}	$m*V_1*V_1*1/2$	The kinetic energy of the train at state 1
E_{kin2}	$m*V_2*V_2*1/2$	The kinetic energy of the train at state 2
E_{kin3}	$m*V_3*V_3*1/2$	The kinetic energy of the train at state 3
E_{kin4}	$m*V_4*V_4*1/2$	The kinetic energy of the train at state 4

Table 9. Description of the forces and flows until the end of the process

Name	Type - Value	Explanation
IIoTE	IIoT	The flow to E0
IIoTE1	IIoT1	The flow to E1
IIoTE2	IIoT2	The flow to E2
IIoTE3	IIoT3	The flow to E3
IIoTE4	IIoT4	The flow to E4
En0	En0E0 = Etr_r+Erub	Determines the amount of energy opposing the move of the train
En1	En1E1 = Etr_r+Erub	Determines the amount of energy opposing the move of the train
En2	En2E2 = Esl+Etr_e+Etl+Erub	Determines the amount of energy opposing the move of the train
En3	En3E3 = Esl+Etr_e+Etl+Erub	Determines the amount of energy opposing the move of the train
En4	En4E4 = Esl+Etr_e+Etl+Erub	Determines the amount of energy opposing the move of the train
Ep0	Ep0E0 = Ereg+Ekin	Determines the amount of energy assisting the train to move

Ep1	Ep1E1 = Ereg+Ekin1	Determines the amount of energy assisting the train to move
Ep2	Ep2E2 = Es+Einv+Erec+Ereg+Ekin2	Determines the amount of energy assisting the train to move
Ep3	Ep3E3 = Es+Einv+Erec+Ereg+Ekin3	Determines the amount of energy assisting the train to move
Ep4	Ep4E4 = Es+Einv+Erec+Ereg+Ekin4	Determines the amount of energy assisting the train to move
s0	E0/15	Distance traveled for the time of 15h
s1	E1/15	Distance traveled for the time of 15h
s2	E2/15	Distance traveled for the time of 15h
s3	E3/15	Distance traveled for the time of 15h
s4	E4/15	Distance traveled for the time of 15h
E0	Ep0E0 + IIoTE + En0E0	The amount of energy
E1	Ep1E1 + IIoTE1 + En1E1	The amount of energy
E2	Ep2E2 + IIoTE2 + En2E2	The amount of energy
E3	Ep3E3 + IIoTE3 + En3E3	The amount of energy
E4	Ep4E4 + IIoTE4 + En4E4	The amount of energy

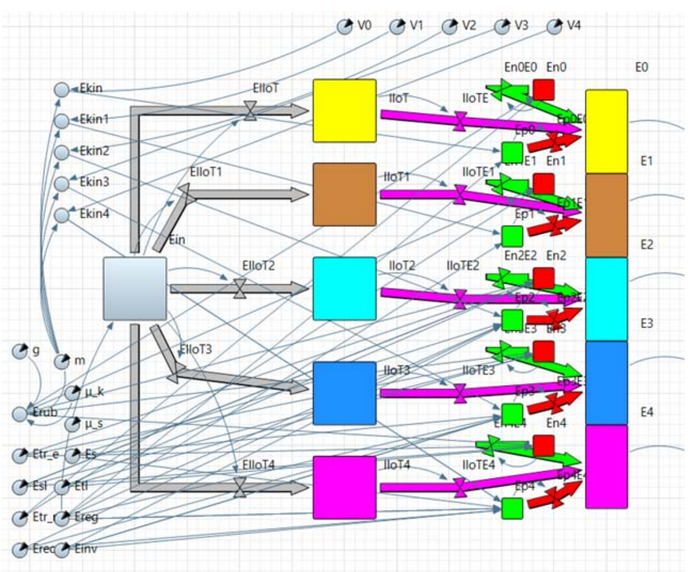

Fig. 7 Simulation Model

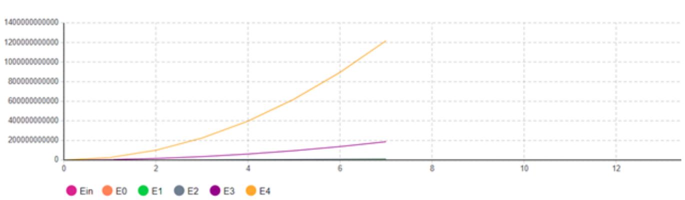

Fig. 8 Diagram of the actions developed at t=7.5h (mid-motion)

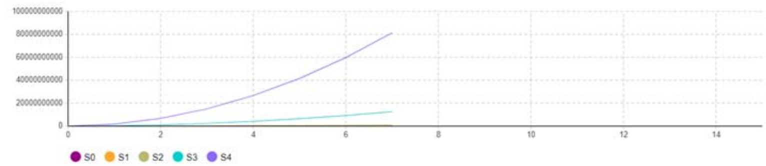

Fig. 9 Diagram of the distance traveled by train type at t=7.5h (midway)

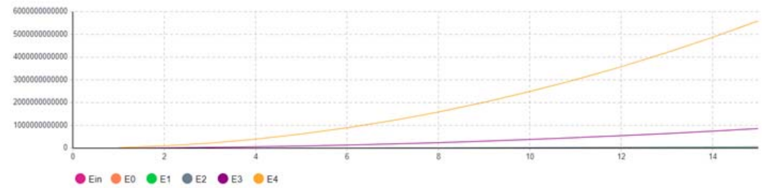

Fig. 10 Diagram of the actions developed at t=15h (after motion)

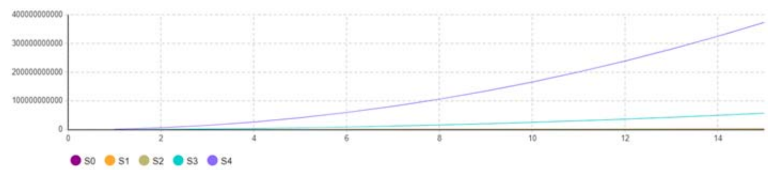

Fig. 11 Diagram of the distance traveled by medium at t=15h (after movement)

5. Conclusion

In this paper, a holistic modeling and simulation method was presented to evaluate the train and its progress through the industrial revolutions that followed its creation. The whole process concerns the movement of the train including those affecting the power system on a case-by-case basis, taking into account the different characteristics that each era had (coal, electricity, etc.) as well as the exclusion of thermal losses that may be applied by their nature to the drone.

At the end of the simulation, the distance traveled by each train was calculated in proportion to the speed it manages to develop. The simulation has been run for a duration of 15 minutes of train movement. The study in question was based on the study of [19], which is essentially based on a subway line in Singapore. The results suggest that the train of the 1st industrial revolution is superiorly faster and consequently the energy it gathers at the end of the movement, than what first appeared in the middle of the 19th century and in particular $E1 \approx 2.13*E0$.

The trains of the 1st and 2nd Industrial revolutions show several similarities, even $E2 \approx 3.5747*E1$, that is, almost four times as much energy was produced during the movement of the train of the 2nd Industrial revolution.
Regarding the rest of the results, it can be seen that $E3 \approx 14.25*E2$ while $E4 \approx 6.512*E3$. In conclusion, the 3rd industrial revolution was launched compared to the previous ones and this is obviously due to the appearance of electricity in the first place but also to the increase in speed

which results in the almost nullification of the resistance forces acting on the system.

Finally, the difference between the train of the 4th industrial revolution compared to the one that first appeared in the year 1804 lies in E4≈706.8*E0, which is due to the aforementioned appearance of electricity but also to the improvement of construction materials.

The reliability of a modern train can be assessed and anticipated based on simulation and evaluation, which can be investigated in the future. It is possible to examine and optimize the health and useable life of support and maintenance equipment by improving train operation and infrastructure design.

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