Practical guidelines for Life Cycle Assessment applied to railways project

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Abstract

Current transport systems are not likely to be sustainable, since energy resources may be less accessible, facing a rapidly growing demand and because of environmental constrains. In this context a great interest arose for sharing environmental assessment practices between infrastructures owners and researchers. For this present work a partnership between RFF and Ifsttar was decided to study environmental effects and energy consumption for railways life cycle. It paves the way to a full life cycle analysis (LCA) for environmental burdens of railway infrastructures and aims at identifying the best design practices at the project level related to environmental criteria. This LCA takes into account earthwork, railway structure and the operation phase, i.e., the analysis performed is based on the estimation of energy consumptions due to construction, maintenance and on the traffic. Results of this work could enhance practices for environment preservation for the plan of building 4000 kilometres of new high-speed railways, decided in the French National Transport infrastructure scheme. Applying LCA to the project phase is a rather new approach. It requires defining a global functional unit as a basic hypothesis of any study, different from the previous studies. Then, the lifecycle subsystems are successively investigated (construction, maintenance and use) to determine the best way for project Functional Unit definition and further assessment method application.

1. INTRODUCTION

1.1 Context and objective

The fact that fossil energy resources are limited and that the demand for these resources is increasing are the basis of the Peak Oil Theory, first introduced as a bell-shaped curve analysis in 1956 by Hubbert [1]. The peak oil occurrence should lead to higher energy prices and lower availability. Moreover, rising demand for fossil fuels would continue to drive up energy - related CO_2 emissions, making it all but impossible to achieve the 2°C goal [2]. These projections reinforce the need to model the energy consumption of transport operation phase in the perspective of energy optimization. In France, a workgroup on national environmental stakes -“the Grenelle of the Environment”- has set ambitious goals for transport systems in many areas such as biodiversity, natural resources and climate change. The French National Transport infrastructure scheme was set up in 2011 according to this, and, in particular, it was planned to build 4000 kilometres of high speed railway. In order to optimize these new investments, RFF, the manager of the French railway network, and the French institute of science and technology for transport, development and networks (Ifsttar) launched a common study concerning a complete life cycle analysis (LCA) of railways, including the energy consumption during the operating phase as a parameter for environmental optimization.

The expected results of this optimization are: the reduction of environmental global effects of infrastructures considering geometry and construction; the sparing of natural resources (including energy and water); the reduction of emissions (green house gases, carbon monoxide (CO), lead (Pb), particulate matter (PM),...); the reuse of deconstruction materials in comparison to other possibilities; the development of a method prior to designing the railway line.

Goals and scope of the study are to find out the Functional Unit (FU) best fitting the requirements of such a minimization before starting calculations. It then arose that considering each subsystem of the project (earthworks, rail construction, maintenance and use in relation with the global line geometry) should be investigated in terms of infrastructure key parameters.

1.2 LCA of railways infrastructures: specificities and literature review

Since the 90’s, at the international level, Life Cycle Analysis has been considered by road civil engineers and public institutions workers as an efficient way to improve road design. It is a standardized environmental assessment method, which has been developed since 1970 for products manufacturing improvement by USA chemical industries and also for packaging industry in Northern Europe and Switzerland. LCA proved to be well adapted for large numbers of manufactured products. It requires the use of a generic functional unit that accurately defines the product properties and functionalities to consider. LCA proved in road framework [3] to be a method for environmental progress according to results obtained on materials processing and mix design (temperature in hot mix plants, recycling, binder content). Hence examining the part of each process in road construction operation helps to highlight the best practice.

Applied to the present study, the life cycle of railway infrastructure consists of three main phases:

- **Construction phase** including three stages of the life cycle: production of materials (raw materials extraction, manufacturing and processing), materials and machines transport, implementation required for the infrastructure construction (in theory, production of machinery should also be included. In practice, it has been removed after applying cut-off rules);
- **Operation and maintenance** phases corresponding to the use of the infrastructure with train traffic and maintenance during life use phase;
- **End of life**. At the end of life phase, the infrastructure is demolished. Demolition materials are transported, treated and recycled or stored.

Existing environmental studies on railways are relatively recent [4-10] and often aim to compare different modes of transport. Thus, Chester and Horvath [8] found that for high-speed rail system, energy infrastructure consumption is about 5% of the train consumption according to rate of occupancy.

Some authors have rather evaluated environmental impacts of alternative structural materials or alternative solutions of construction to lower consumption of energy, natural resources use and emission of pollutants [11-12]. One of the constructive solutions especially analyzed [13-15] is the ballastless slab track *vs*. ballasted track. Such ballastless technology does not necessarily increase the total energy consumption of the infrastructure [13] given its 60 years life and its low maintenance. Nevertheless the NetworkRail study [15] seems to indicate the opposite, ballastless slab track emitting significantly more emissions than ballasted track. In such case the technological issues are rather studied and concentrate more on structure design Of course this study aims at investigating this issue but it is not the only one. Hence to go further on this topic, and as this study focuses on ecodesign, a functional unit (FU) suitable to this study would be "a double track high speed railway of 400 km with travel time of 1 h 50 mn and with 40 trains per day for each track during 50 years". This functional unit is composed of the following elementary functional units (Fu):

- Fu 1 = about 400 earthwork units composed of cut and fill; an earthwork unit is a 1 km area worked to obtain either cut or fill (subgrade soil, capping layer);
- Fu 2 = about 488 civil engineering structures including one tunnel;
- Fu 3 = about 400 km of sewer drainage system;
- Fu 4 = about 300 km of road rehabilitation;
- Fu 5 = about 400 km of railway foundation (sublayer);
- Fu 6 = about 400 km of railway equipment (ballast, sleepers, signing equipment, catenaries, substations);
- Fu 7 = about 400 km of traffic and maintenance railway.

In this paper, preliminary results on Fu1, Fu5 and Fu7 are given.

1.3 Outline

The original feature of this present study is then to optimize the design of infrastructures while taking into account earthwork, structure and operation phase within LCA frameworks.

After the introduction, the second section of this article is about the construction phase. This section has two parts. The first one deals with earthwork, a step which has not yet been investigated in the literature through LCA studies. The second one is about the structure (layers above the earthwork). The third section of the article presents the methodology used to assess the operating phase; an experiment on the Rhine-Rhone high-speed railway line is presented. The methodological issues for high speed line assessment are based on a selection of impact categories and will be done as soon as energy contributions to life cycle will be analyzed.

2. CONSTRUCTION

Concerning public works, the better consideration of environmental issues has led to the progressive incorporation of environmental criteria into public calls for tenders. In this context, the strategy of IFSTTAR was to develop the LCA tool "ECORCE" (a software tool with a specifically developed database from open references, since 2008) [16], with respect to both the road code of practice and the environment, and finally to adapt the methodology for railways.

The idea is therefore to define indicators enabling the calculation of parameters to assess the environmental effects; prior to describe the principles to minimise environmental loads. This method shall allow the professions concerned to deduce the best compromise between the different technologies.

2.1 Earthwork stage

When considering the potential environmental impacts of the different stages inherent to the railroad construction, the earthwork phase is of crucial importance. As a matter of fact, while the earthwork phase stands for a few percents of total road energy consumption (0.4% of life cycle energy consumption for excavation and 1% for entire construction site energies, [13]), it may account for a significant fraction of other impact indicators like human chronic toxicity potential ($I_{TP,}$ [17]). The earthwork phase also affects the ecological state of the adjoining and global environment: i) it suddenly sets a barrier that fragments the habitats, ii) it alters the behaviour of the local micro / macro-fauna through the earthwork yard avoidance and disturbance (e.g. noise, soil, water and air pollutions) and iii) it allows alloctonous species / plants to reach previously inaccessible areas and therefore modify the interactions between authigenic organisms. The magnitude of the induced impacts vastly depends on the geomorphology and thus on the consumed amount of fuel relative to cuts and fills. Based on a previous study devoted to road earthworks for a 8.9 km long area, earthworks units of 1 km were defined as a reasonable unitary entity to deal with for assessment [18]. Hence, in order to assess the influence of the geomorphology of soils, the earthwork organization has been monitored for a several-years long period. First, the volumes of cuts and fills were analyzed for every single earthwork items. Then, the fuel consumed by machines was determined as a function of their type, daily work and corresponding earthwork item (see items in Table 1). This was a complex task since the earth engineering machines work cannot be easily isolated at one time, as all the materials excavated and compacted are moved continuously. The obtained figures pointed out that the fuel consumed per cubic meter of moved earth increased linearly as a function of the average crossed distance:

$$\text{Fuel consumed (L m}^{-3}\text{)} = 3.3\ 10^{-4}\ \text{Distance (m)} + 0.06. \quad (r^2 = 0.97)$$

Finally, the amounts of imported materials (e.g. quicklime, aggregates, etc.) were assessed (Table 1).

Table 1 –Data for FU 1 assessment Engineered earth volumes (i.e. total cuts volume) and fuel consumptions for moved earth relative to the different earthwork items constitutive of a typical earthwork.

Earthwork item For 400 km	Engineered earth volume (m^3) extrapolated from [18]	Distances crossed by m^3 of moved earth* (average ± S.D.) (m) from [18]	Diesel fuel consumed per m^3 of moved earth (L) [18]	Equivalent energy to diesel fuel consumed extrapolated for FU 1 (Mj)
Treated sub-base layer	9.9E+05	900 ± 260	0.31	1E+07
Unusable cuts†	4.9E+06	770 ± 190	0.34	7E+07
Treated fills	3.6E+06	1360 ± 450	0.53	7E+07

Revegetation	7.6E+05	50 ± 30	0.08	2E+06

*The moved earth accounts for the part of engineered earth that was not locally processed.
† The unusable cuts are locally stored as lateral earth walls and/or noise barriers

Based on such obtained relationships, researches are currently led in our laboratory in order to assess the potential environmental impacts and fuel consumptions for various earthwork designs. In details, the previous researches aimed at answering to the following questions. What is the relative contribution of the earthwork phase to the environmental impacts (with respect to these of the railroad structure construction, usage and maintenance)? How should the railroad track be designed in order to minimize the environmental impacts and fuel consumption relative to the earthwork phase? How does the earthwork geometry (e.g. the frequency of cuts and fills, distance crossed by moved earth, slope) and employed construction techniques affect the local environmental and the life cycle assessment for railroad construction?

2.2 Railway structure construction

Construction scenarios –materials production (FU 5)

The objective of the environmental assessment is to compare different structures. The variable elements must only be those corresponding to changes in structures and their possible consequences. The section covered by the scenario will thus be considered with the same longitudinal section; with the same use so that the design is made for a line carrying the same traffic; on the same construction site; with the same use phase (Fig.3).

Considered scenarios relate to the construction of high-speed railway infrastructure and have been previously defined in a working session with experts of RFF. Two main types of scenarios of ballasted track are considered and are referred as "Scenario 1" and "Scenario 2." The major difference between these two scenarios lies in the material of the sublayer (Fig.3):

- Graded aggregate (0/31.5) for scenario 1 corresponding to the current conventional railway construction;
- Bitumen-bound graded aggregate (0/14) for scenario 2, a material which has been spread on some parts of the French high-speed railway, “LGV East”, for a test. This material seems interesting for absorbing vibrations transmitted to the ballast and mechanical performance improvement is expected i.e. ballast life time.

Table 2 – Data for FU5 and capping layer part of FU1 assessment – materials energy consumption (EC) and Global-warming potential (GWP) according to the two scenarios.

Indicators	**EC (MJ)**	**GWP (t.eq.CO2)**
Scenario 1	5E+8	6.5E+4
Scenario 2	1.25E+9	6.8E+4

For both scenarios, the ballast layer (31.5/50) will have the same thickness, equal to 35 cm under sleepers. The structure will also be identical and consisting of prestressed concrete monoblock sleepers (1666 sleepers per km); Vignoles 60 E1 rails; fastening systems. The width of the railbed is 15m. The results are given in the Table 2. They are computed with Ecorce from Data given in [19].

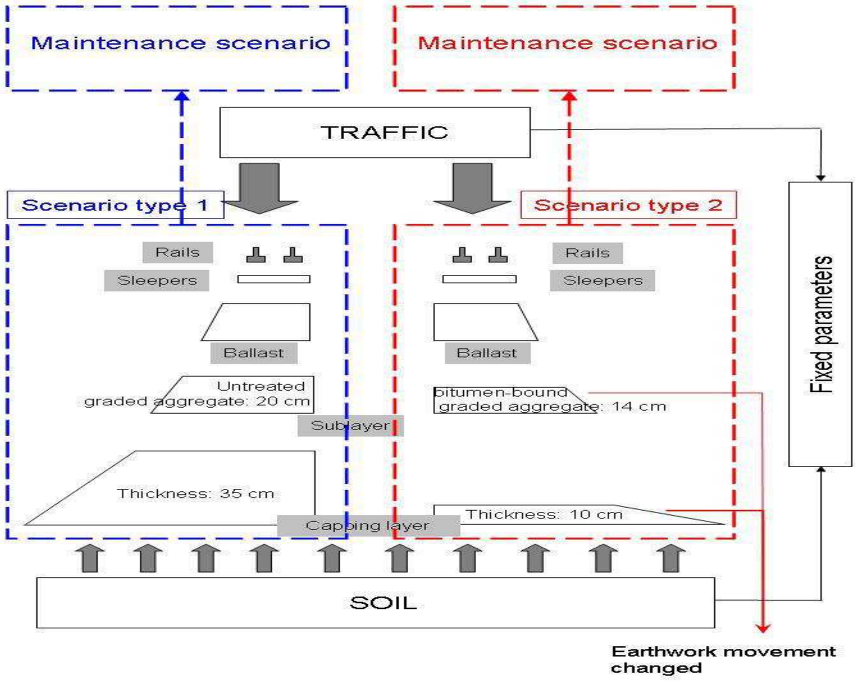

Figure 3 Synthetic scheme for scenarios selection

For the scenarios 1 and 2, the vegetation control scenarios correspond to the "classic" scenario on high-speed railway and are as follows:

- Scenario 1: Three annual passes of weed-killing train are considered. Chemicals used are either foliage-applied herbicides (curative treatments), soil-applied herbicides (preventive treatment) or brush killers.
- Scenario 2. This construction scenario may change the "classic" scenario of vegetation control. According to experts from the French National Railway Company, SNCF, the changes adopted are: "a 10 to 14-cm thick bitumen-bound graded aggregate is a naturally resistant support to vegetation development and allows, if applied to the whole platform, to avoid any phyto-sanitary treatment ".

This could show the interaction between construction technique and maintenance and has to be assessed in future work

Scenarios of track maintenance (part of FU7)

Two different maintenance scenarios were selected from current practices on the existing network. Thus, we consider a first scenario 1-m1 of maintenance corresponding to a speed level reaching 300 km/h and a second, called 1-m2, for a traffic speed of 320 km/h. According to the background of LGV East, for a traffic speed of 320 km/h, the maintenance operations for ballast tamping apply to 85% of the line each year, instead of 58% for the 300 km/h scenario 1. These additional maintenance operations could cause premature wear of ballast, which would imply a 15% ballast consumption increase.

A first estimation can be examined through simple calculations as follows;

Scenario 1-m1 = Impacts of construction x 0.85   at 320 km/h

Scenario 1-m2 = Impacts of construction x 0.58 at 300 km/h

Transport scenarios for materials (part of FU 7)

For some materials, such as ballast with a large tonnage, different transport scenarios will be considered involving the following modes, Boat; Train; Road. At this time a precise system should be defined to obtain the right order of magnitude of this sub system.

3 EVALUATION OF ENERGY CONSUMPTION DURING THE OPERATING PHASE

3.1 Energy evaluation methodology

To estimate the energy consumption, the train is considered as a point with a mass M. Newton's second law is applied to this point (see the equation (1)). This gives the power required by the train. Then the electric consumption is deduced by using a constant ratio which illustrates the efficiency of the traction system, including electric motor and mechanical traction.

$$kM \bullet \gamma = F j - R - M \bullet g \bullet \sin(\alpha). \quad (1)$$

M is the train mass, k the inertia coefficient of rotating masses; γ the longitudinal acceleration; α the slope, F j the force delivered by the electric motor to the drive wheels.

R is the resistance force which is composed of:

- Rolling resistance, related to the wheel-rail contact;
- Mechanical resistance, consisting of varying viscous friction Fv and dry friction Fs,
- Aerodynamic resistance, related to drag coefficient Cx, and weather conditions.

This resistance force is detailed in [20] and has, generally, the following form:

$$R = A + B \bullet V + C \bullet V^2 \quad (2)$$

V is the train velocity; A, B, C: coefficients depending on rolling stock and infrastructure.

3.2 Full scale experimental tests for model validation

The trial runs on the new Rhin-Rhone high-speed railway line were carried out during June, July and August 2011. During these tests, geometry, energy and dynamic measurements were performed. Direction and velocity of the wind were recorded too.

The previously presented model (eq (2)) has been validated upon these experimental tests [21] the average estimated consumption is 79.9MJ per kilometre as the average measured consumption is 75.9MJ per kilometre. This result enables us to compute the assessment of FU7 for the energy consumption (see Table 3). This is consistent, in terms of magnitude with Janic [22] by example who gives a consumption of 68.4 Mj per kilometre for a TGV (French train) and 79.6 Mj per kilometre for an ICE (German train), given the fact that the actual speed is higher than the speeds given in [22]. About 80% of consumed energy is used to compensate the resistance force.

Thanks to this model, it is possible:

- To investigate the influence of a chosen geometry path to the energy consumption;
- To calculate the interest to get a rolling stock having energy regeneration brakes;
- To calculate the influence of the speed references to the energy consumption.

Table 3 –Data for FU 7 assessment about 400 km of traffic (40 trains per day for each track during 50 years) considering energy consumption (EC) and Global-warming potential (GWP)

Indicators	**EC (MJ)**	**GWP (t.eq.CO2)**
Traffic	1.6E+12	5E+7

4 CONCLUSION

A possible functional unit was investigated in this paper for high-speed railway ecodesign. Based on former road experience and new train data collected for this study, some orders of magnitude of energy assessment and GWP were determined to validate the framework and some guidelines.

Due to environmental constrains on the existing transport system, several railway projects were launched. For consistency sake, these projects have to be assessed from an environmental point of view. In this paper, we propose a methodology to apply life cycle assessment, to railway projects with a special focus on the construction phase and the operation phase. A method is proposed to quantify the energy spent on the earthwork stage by modeling earth moving. Concerning the structure, two scenarios of construction are presented. The first scenario is classical aggregate subbase, when the second one includes a layer of bitumen bound aggregates. Concerning the operation phase, the electrical consumption due to the traffic on the infrastructure is evaluated. The next step of this work will consist in taking into account the maintenance. The final goal is to propose a tool allowing a global comparison of different projects including different techniques of construction and different geometries.

ACKNOWLEDGEMENTS

This work has been achieved with the collaboration of experts from RFF, particularly O. Cazier and A. Grux.

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