Sustainability of Railway Passenger Services – A Review of Aspects, Issues, Contributions and Challenges of Life Cycle Emissions

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Abstract
This paper presents a review of research and models regarding sustainability of railway passenger services. In order to take into account all relevant aspects in terms of environmental impacts of a railway passenger service, a holistic system perspective is required, that includes a whole life cycle assessment. A life cycle approach is important since comparison of for instance only the exhaust emissions of an electric vehicle with a petrol vehicle is misleading, due to neglecting the emissions of for instance electrical energy production process. Thus, all stages in energy carrier, vehicle and infrastructure life cycles are to be considered. Existing models are analyzed, as well as possible developments, focusing on diesel and electrical traction as the most common traction options in use, and on GHG emissions, especially on CO_2, which takes the greatest part in all emissions. Issues and challenges in improving the environmental impact of railway passenger services are addressed. Additionally, several areas are indicated where environmental aspects could be included in future assessment models. The main challenge is answering how the existing partial assessments can be brought together and, together with filling the identified gaps, allow to conduct a comprehensive LCA which will produce real-world emissions estimations. Results of this paper will be used as an input in developing a framework for quantifying and improving overall environmental impacts of a railway passenger service.

Keywords
Railway transport, Sustainability, Environmental pollution, CO_2, Life cycle assessment

1 Introduction

“Sustainable Transportation” is a widely discussed and researched topic. Starting from the report titled “Our Common Future” of the Brundtland Commission (UN, 1987), in which the sustainable development is defined as a “*development which meets the needs of current generations without compromising the ability of future generations to meet their own needs*”, a number of initiatives and studies have been conducted in the transport industry. Reference is often made to the three ‘dimensions’ or ‘pillars’ of sustainability – namely the environment, the economy, and society/social equity. However, the majority of studies so far prioritized economic aspects.

The transport sector, as one of the largest contributors in global greenhouse gas (GHG) emissions, is especially affected by the increased concerns for the environment in the last decade(s). Carbon dioxide (CO_2) takes the largest part in all GHG emissions from transportation, more than 95%, while other most represented GHGs include methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFC) and perfluorocarbons (PFC) (EU, 2017). In quantifying the amount and the composition of emitted GHGs, in order to make different types of GHGs comparable, a so called CO_2 equivalence factor ($CO_{2\text{-eq}}$) is defined for each of them (IPCC, 2007). This factor expresses the global warming potential (GWP) of one unit of a GHG compared with one unit of CO_2. For instance, N_2O has a $CO_{2\text{-eq}}$-factor of 298, i.e. one ton of N_2O has the same global warming effect as 298 tons of CO_2 (EC, 2014). Globally, the railway sector was responsible for 1.9% of transport-related final energy demand, and for 4.2% of CO_2 emissions from the transport sector in 2015. Following the UN's Paris Climate Agreement from 2015 (UN, 2015), the EU's overall goal is to reduce GHG emissions from transport by 2050 to a level that is 60 % below that of 1990 (EEA, 2017). For the railway sector targets are set by the UIC (International Union of Railways) and CER (Community of European Railway and Infrastructure Companies), with the short term target on decreasing CO_2 emissions by 30% over the period 1990 to 2020, with a further decrease by 50% in 2030 (UIC, 2012).

Taking into account the global tendency in modal shift to railways, the environmental impact of this mode of transport should be given more attention. In their "5E" framework which is used to quantify the value of public transport using five E's (Effective mobility, Efficient city, Economy, Environment, and Equity), Van Oort et al. (2017) showed that one of the main potential benefits of modal shift to railways regards environmental aspects. Technological progress is also made in recent years with the introduction of alternative fuels. However, comprehensive studies which would encompass the whole life cycle and give the insights in total impact of the novel energy options for railways are lacking in the literature.

In this paper, a review that highlights and analyzes the contributions in environmental sustainability related to passenger railway services is presented. Existing models are reviewed, as well as possible developments, focusing on diesel and electrical traction, as the most common traction options in use, and on GHG emissions, especially on CO_2, which takes the greatest part in all emissions. Additionally, main issues and challenges are addressed and several areas are indicated where environmental aspects could be included in future assessment models.

Section 2 introduces existing emissions assessment approaches and outlines the differences between them. Section 3 reviews the literature on the direct emissions estimations for railways. Section 4 gives the review on railway Well-to-Wheel (WTW) analyses. Section 5 reviews the railway Life Cycle Assessment (LCA) studies. Discussion on the main findings is given in section 6. Finally, section 7 ends this literature review with the main conclusions and provides the future research directions.

2 Railway Emissions Assessment Approaches

Emissions as a consequence of railway service operation are closely related and are directly influenced by the energy consumption. Thus, in most railway emissions assessments energy use and emissions estimation are carried out simultaneously. In general, all the emissions from the railway service operation can be divided into direct emissions (e.g. from diesel consumption in the combustion engine, usually referred as the consumption phase) and indirect emissions (e.g. from energy carrier production and delivery and the construction/production and maintenance of infrastructure and vehicles).

A number of approaches in emissions assessment have been developed and applied, and the selection of the adequate method is influenced by numerous factors and aspects, such as the goal and scope of the study, system boundaries, data availability, does the study represent *ex ante* or *ex post* evaluation, etc. In general, two main categories of research methods for calculating energy use and emissions per transport unit can be distinguished (Van Wee et al., 2005):

- 'Bottom-up' methods (BUMs), which explicitly include determinants such as weight, resistances, speed, etc.; and
- 'Top-down' methods (TDMs), which use aggregated data in calculations by dividing total energy use and emissions by the selected transport indicator, i.e. tons of $CO_{2\text{-eq}}$ / passenger-km.

Regarding the scope and system boundaries of the study, a number of studies limited their scope on direct emissions from the consumption phase (Papagiannakis and Hountalas, 2003; Lapuerta et al., 2008; Papagiannakis et al., 2010a; 2010b; Johnson et al., 2013). In order to take into account all relevant aspects in terms of environmental impacts of a

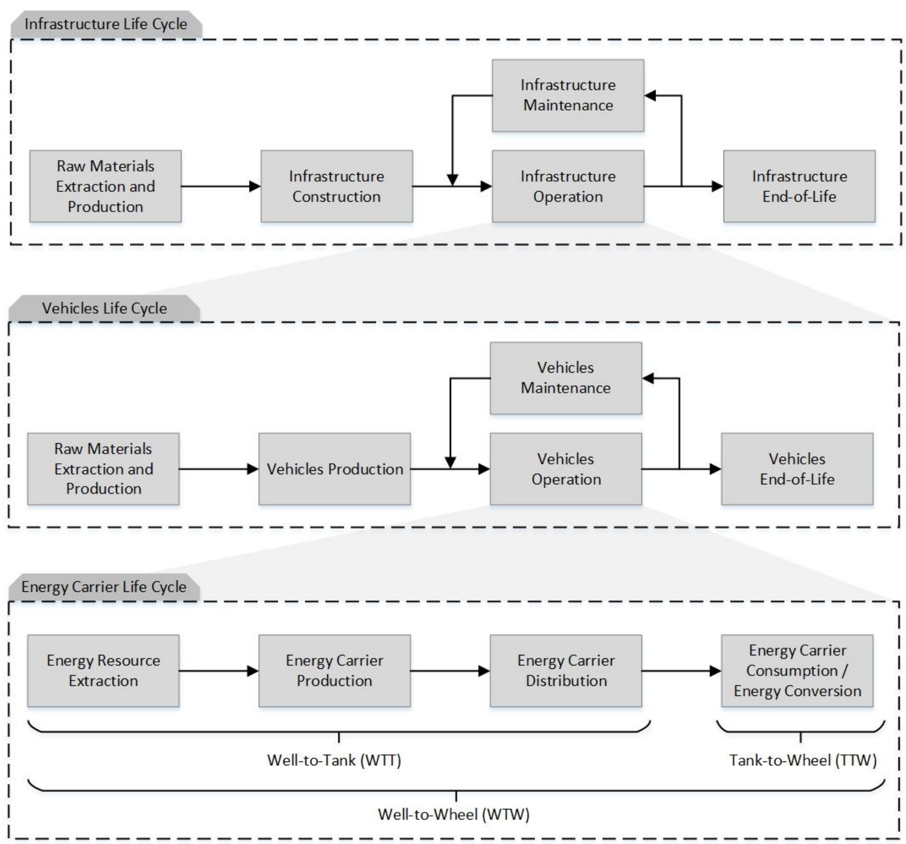

Figure 1: Infrastructure, Vehicles and Energy Carrier Life Cycle

passenger railway service a holistic system perspective that observes the whole life cycle (emissions from all stages in energy carrier, vehicle and infrastructure life cycles) has gained great importance in the recent years. The complete infrastructure, vehicles and energy carrier life cycles with the main corresponding processes are presented in Fig. 1.

The life cycle approach is important, because, for instance, comparison of only the exhaust emissions of an electric vehicle with a petrol vehicle is misleading, due to neglecting the emissions from electrical energy production, especially if the primary resource is i.e. coal. A holistic approach helps in better understanding of energy consumption and associated CO_2 emissions by analyzing these aspects throughout the whole life cycle of the system, instead of only considering the consumption phase.

Studies that observe the whole energy carrier pathway employ the so-called Well-to-Wheel (WTW) approach. WTW analyses are divided into two stages, as depicted in Fig. 1: (i) Well-to-Tank (WTT) stage, consisting of energy resource extraction, production and distribution processes; and (ii) Tank-to-Wheel (TTW) stage, also referred as the vehicle operation phase, or the consumption phase (Hoffrichter et al., 2012). The WTW approach neglects infrastructure construction and vehicles production, as well as infrastructure and vehicles end-of-life processes (recycling and disposal), and it represents a subclass of a wider-scope Life Cycle Assessment (LCA) approach (Orsi et al., 2016). LCA observes the complete infrastructure and/or vehicles pathway, and in most cases explicitly or implicitly encompasses all the processes included in WTW.

The organization of this review paper is based on the scope and system boundaries criteria, where the following three sections provide a review on: (i) studies and approaches focused on the direct emissions from the consumption phase; (ii) WTW analyses which observe energy carrier life cycle; and (iii) LCA studies which encompass infrastructure and/or vehicles life cycles and associated emissions.

3 Direct Emissions from the Consumption Phase

A number of studies has limited their research on the consumption phase, in particular on direct energy consumption and related emissions. Two different approaches for estimating emissions in this phase can be identified in the literature: (i) applying direct on-track or laboratory measurements, using modern equipment, sensors, etc.; and (ii) applying mathematical models and numerical calculations.

3.1 Emissions Obtained from Direct Measurements

Direct measurements in assessing emission levels is in most cases applied in testing engines powered by different liquid and gaseous fuels, such as diesel, bio-diesel, or natural gas using modern measuring equipment. These measurements are in most cases project-tailored and represent expensive and extensive experiments. Although usually case-specific, the results of these studies can be very useful in future research, either in the assessment models development or in results validation. Existing studies in the literature and their main findings are given chronologically in the remaining of this sub-section, as follows.

Papagiannakis and Hountalas (2003), Papagiannakis et al. (2010a, 2010b) conducted an experimental investigation to examine the effects of the emissions of a high speed, compression ignition engine where liquid diesel fuel is partially substituted by natural gas in various proportions, with the natural gas fumigated into the intake air. The experimental results disclose the effect of these parameters on nitric oxide (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC) and particulate matter (PM) emissions, with the beneficial effect of the presence of natural gas being revealed. They conclude that dual fuel combustion using natural gas as a supplement for liquid diesel fuel is a promising technique for controlling both NO_x (decrease up to 47%) and PM emissions on existing diesel ignition engines, requiring only slight modifications of the engine structure. The observed disadvantages are an increase in HC and CO emissions that can be possibly mitigated by applying modifications on the engine tuning, e.g. injection timing of liquid diesel fuel mainly at part loads.

In 2006 Rail Safety and Standards Board (RSSB) and the Association of Train Operating Companies (ATOC) investigated the use of bio-diesel on Britain's railways and published a report on August 2010 (RSSB, 2010). The effects on the engine's performance and exhaust emissions were tested using increasing biodiesel blending. The engines were tested under laboratory conditions on a range of blends of bio-diesel, from 5% bio-diesel (B5) in steps up to 100% bio-diesel (B100). Based on the results, it has been concluded that B20 (a 20% blend of bio-diesel mixed with 80% diesel) was sensibly the highest blend that could be accepted without significant expenditure to retune engines. The use of B20 did not appear to cause any significant engine wear, but the fuel consumption performance was worse. Generally when using bio-fuel: the fuel consumption increased; NOx levels tended to increase; the total HC emissions tended to decrease; CO and CO_2 emissions were less consistent throughout but tended to be lower than for diesel; the PM and exhaust smoke decreased.

Lapuerta et al. (2008) collected and analyzed papers published in scientific journals about diesel engine emissions when using bio-diesel fuels as opposed to conventional diesel fuels. The first section is dedicated to the effect of bio-diesel fuel on engine power, fuel consumption and thermal efficiency, while the second section focus on the comparison of engine emissions from bio-diesel and diesel fuels, paying special attention to the most concerning emissions: NO_x and PM, the latter not only in mass and composition but also in size distributions. In this case the highest consensus was found in the sharp reduction in PM emissions.

Xue et al. (2011) analyzed reports about bio-diesel engine performance and emissions, published by highly rated journals in scientific indexes since year 2000. The effects of biodiesel on engine power, economy, durability and emissions including regulated and non-regulated emissions were analyzed. It was found that the use of bio-diesel leads to substantial reduction in PM, HC and CO emissions accompanying with a small power loss, increase in fuel consumption and increase in NO_x emissions on conventional diesel engines.

Poompipatpong and Cheenkachorn (2011) modified a diesel engine for natural gas operation and evaluated the emission and power output effects of such modifications. They also mentioned that two of the advantages of natural gas are clean combustion and attractive price. They tested the emissions of CO, THC and NO_x for different compression ratios and compared the results.

Abdelaal and Hegab (2012) tested a single-cylinder direct injection (DI) diesel engine on regular operation and dual-fuel mode, with natural gas as the main fuel and diesel fuel as a pilot. Comparative results of exhaust emission were presented for several operating modes. They mentioned natural gas as a partial supplement for diesel fuel as a very promising solution for reducing pollutant emissions, particularly NO_x and PM. The results showed reduction in NO_x and CO_2 emissions, while CO emissions increased.

In 2012, Clean European Rail-Diesel (CleanER-D, 2012) delivered a report on the impact and performance of alternative fuels in rail applications. The main objective was to study the different types of fuel used in railway applications and their effect on engine parameters. It was found that bio-diesel blends up to 20% are technically feasible although increasing fuel consumption compared to diesel.

Park et al. (2012) examined the PM characteristics of diesel locomotive engine exhaust at various engine ratings. Diesel engine exhaust was collected via a dilution tunnel and the concentration and size distribution of fine particles were measured by a scanning mobility particle sizer. The results showed that the maximum CO emission was reached at 59% of the maximum rating, after which emissions decreased.

Johnson et al. (2013) described and applied a technique for analyzing exhaust emission plumes from unmodified locomotives under real world conditions from railway trains servicing an Australian shipping port. The method utilized simultaneous measurements downwind of the railway line of the following pollutants: particle number, PM, mass fraction, SO_2, NO_x and CO_2, from which emission factors were then derived. Samples from 56 train movements were collected, analyzed and presented. The quantitative results for emission factors were noted and the findings were compared with previously published papers. Statistically significant correlations within the group of locomotives sampled were found between the emission factors for particle number, SO_2 and NO_x.

3.2 Emissions Obtained from Numerical Calculations

Obtaining emission levels by means of numerical calculations can be done using both TDMs and BUMs. TDMs are usually used for direct emissions calculation in WTW or LCA studies, since they use aggregated data and are easily incorporated in wider scope studies. Most commonly used BUMs in calculating the emissions of rolling stock in the consumption phase are through energy consumption calculations based on resistances. Since the large majority of the energy used by the train (≈80%) is to overcome resistances that the train is subject to when traveling along the track, once these resistances are known they can be multiplied by the distance traveled in determining total energy consumption (Network Rail, n.d.; SYSTRA, 2011). Once energy consumption needed for overcoming the resistances is calculated, it then can be multiplied by the emission factors in order to obtain the total emissions of the train.

All resistances can be split into two categories: (i) inertial/grade resistances, which account for the infrastructure characteristics, and are independent of the train; and (ii) running resistances, which depend on train characteristics and train speed (UIC, 2003). Running resistances of a train can be modelled using the standard Davis Equation (Davis, 1926):

$$R = A + Bv + Cv^2 \tag{1}$$

where R is resistance (N), v is speed (m/s), and A, B and C are coefficients specific to the train obtained from the experimental data, where A is proportional to the mass of the train and accounts for the bearing resistances, B accounts for the rolling resistance and C for the air resistance.

Esters and Marinov (2014) identified three different existing methods for energy consumption calculation based on resistances and applied them in calculating emissions of UK rolling stock. The three methods for energy consumption calculation are: (i) the International Union of Railways (UIC) method, (ii) the Rail Safety and Standard Board (RSSB) method, and (iii) the ARTEMIS rail emissions model. Although they all start from the standard Davis Equation given in (1), the coefficients and amount of data required for their implementation differs. The three methods are presents in sub-sections as follows.

International Union of Railways (UIC) Method

The UIC methodology (Garcia, 2010) factors the distance travelled into the equations and thus gives the energy consumption directly instead of resistances of the train. Total energy consumption is calculated as:

$$E = E_m + E_a \tag{2}$$

where E_m represents the energy due to mechanical resistances, and E_a the energy due to aerodynamic resistances. Energy consumption due to mechanical resistances depends on the mass of the train and arise due to the contact between the wheels of the train and the track:

$$E_m = (a + a_c) \cdot m \cdot l \tag{3}$$

where a is the coefficient depending on the rolling stock (N/t), a_c is the coefficient depending on the route - number of curves on a track and their length and radius (N/t), m is mass of the train (t), and l is the length of the route (m).

Energy due to aerodynamic resistance (E_a) is expressed as the sum of drag due to pressure forces (E_p) and drag caused by friction (E_f). Energy required to overcome pressure drag is given by:

$$E_p = c_p \cdot S_f \cdot \int T_f \cdot v^2 \cdot dl \tag{4}$$

where c_p is the pressure drag coefficient (N/(km/h)^{2}m^2), S_f is the cross-sectional frontal area of train (m^2), T_f is the tunnel factor, v is speed (km/h), and l is the length of the route (m).

Energy needed to overcome frictional drag is given by:

$$E_f = c_f \cdot S_m \cdot \int T_f \cdot v^2 \cdot dl \tag{5}$$

with c_f the frictional drag coefficient (N/(km/h)^{2}m^2), and S_m the wet surface area (m^2) where the train will feel shear stresses due to the forward motion of the train:

$$S_m = ((2H) + W) \cdot L_t \tag{6}$$

where H is the height of the train (m), W is the width of the train (m), and L_t is the length of the train (m).

Rail Safety and Standards Board (RSSB) Method

The RSSB methodology (RSSB, 2007) uses a specific version of the Davis Formula:

$$R = k \cdot M + (B_1 + B_2) \cdot v + C \cdot v^2 \tag{7}$$

where k is the constant of proportionality, M is the mass of the train (kg), B_1 is a constant which relates to the rolling resistance of the train and is linearly proportional to the mass of the train, B_2 is a constant representing the mass of cooling air and the mass of ventilation air, v is the train speed (m/s), and C is a constant used to describe the aerodynamics of the train, given by:

$$C = \frac{\rho}{2} \cdot C_d \cdot A_x \tag{8}$$

where ρ is the density of air (kg/m^3), A_x is the cross-sectional frontal area of the train (m^2), and C_d is the drag coefficient given by:

$$C_d = C_{dht} + C_{dl} + C_{db} + C_{di} + C_{de} \tag{9}$$

where C_{dht} is the head and tail drag coefficient and is determined by the pressure forces at the head and tail of the train, C_{dl} is the frictional drag coefficient and is linearly proportional to the length of the train, C_{db} is the bogie drag coefficient, C_{di} is the extra drag coefficient dependent on the number of vehicles, and C_{de} is the pantograph drag coefficient used to account for the pressure forces felt by the pantographs on an electric train. C_{dl} is given by:

$$C_{dl} = L \cdot L_f \tag{10}$$

where L is length of the train (m), and L_f is the length factor. C_{db} is given by:

$$C_{db} = 2N_v \cdot B_f \tag{11}$$

with N_v the number of vehicles, and B_f the bogie factor. C_{di} is given by:

$$C_{di} = 0.025(N_v - 1) \tag{12}$$

ARTEMIS Rail Emissions Model

The ARTEMIS rail emissions model (Lindgreen and Sorenson, 2005) uses a fundamental approach to calculating resistance, which is split into two parts. Summing the two resistive forces gives:

$$F_m = F_R + F_L \tag{13}$$

where F_m is the total resistance of the train (N), F_R is the rolling resistance (N), and F_L is the air resistance (N). Rolling resistance is given by:

$$F_R = f_R \cdot m \cdot g \tag{14}$$

where m is mass of the train (kg), g is gravitational acceleration (m/s2), and f_R is the rolling resistance coefficient given by:

$$f_R = C_0 + C_1 \cdot \left(\frac{v}{v_0}\right) + C_2 \cdot \left(\frac{v}{v_0}\right)^2 \tag{15}$$

where C_0, C_1 and C_2 are coefficients, v is the train speed (km/h), and v_0 is the speed constant equal to 100km/h. C_1 and C_2 are constant specific for different train types, and C_0 is given by:

$$C_0 = \frac{f_{sl} \cdot m_l + f_{sv} \cdot m_v}{m} \tag{16}$$

where f_{sl} is the rolling resistance coefficient for locomotive which depends on the number of axles of the locomotive, f_{sv} is the rolling resistance coefficient for carriages, m_l is the total mass of locomotives (kg), m_v is the total mass of carriages (kg), and m is the total mass of the train (kg). f_{sv} is a function of axle load and is given by:

$$f_{sv} = C_{cv} + \left(\frac{F_A \cdot n_{ax}}{m \cdot g}\right) \tag{17}$$

where C_{cv} is a coefficient that depends on the type of vehicle, F_A is an axle pressure constant equal to 100N, and n_{ax} is the total number of axles of carriages.

Air resistance (F_L) has a similar form as in previous methods and is given by:

$$F_L = \frac{\rho}{2} \cdot C_L \cdot A_x \cdot v^2 \tag{18}$$

where ρ is the density of air (1.247 kg/m^3), A_x is the cross-sectional frontal area of train (m^2), and C_L is the drag coefficient calculated by summing the contributions of the carriages and locomotives:

$$C_L = \sum C_{car} + C_{loco} \tag{19}$$

where C_{car} and C_{loco} are the drag coefficients of a carriage and the front loco, respectively. C_{loco} is defined by the number of axles, shape of the locomotive and whether it is an electric or diesel powered train.

The presented models and approaches can be extended by incorporating real conditions that influence consumption and emissions, such as track resistances, driving styles, etc. The effect of regenerative braking could also be included as it contributes in energy savings in case of electric traction. Also optimal energy-efficient train driving and energy-efficient timetabling strategies can contribute in reduction of energy consumed, and thus in total emissions. A comprehensive review of approaches in energy-efficient train control and timetabling can be found in Scheepmaker et al. (2017).

4 Railway Well-to-Wheel Analyses

A Well-to-Wheel (WTW) analysis observes the whole life cycle of an energy carrier (i.e. diesel, electricity, etc.), and can be subdivided into the Well-to-Tank (WTT) stage that focuses on the energy carrier supply chain, and the Tank-to-Wheel (TTW) stage, which covers the vehicle operation (Fig. 1). Many variations of WTW analyses have been proposed in the literature for automotive and bus industry (Yazdanie et al., 2014; Li et al., 2016; Orsi et al., 2016; Correa et al., 2017; Woo et al., 2017; Dreier et al., 2018), mostly applying different modifications of the GREET (Regulated Emissions, and Energy use in Transportation) fuel-cycle model (ANL, 2016), ADVISOR (Advanced Vehicle Simulator) software (ADVISOR, 2003) and other commercial and non-commercial models. On the other hand, the number of studies analyzing railway transportation from WTW perspective is rather scarce. Although WTW analyses are in most cases explicitly or implicitly included in LCA studies, the calculations are based mainly on aggregated data and approximate estimations.

Hoffrichter et al. (2012) evaluated energy efficiencies and CO_2 emissions for electric, diesel and hydrogen traction for railway vehicles on a WTW basis using existing estimations in the literature. They use the low heating value and high heating value of the enthalpy of oxidation of the fuel. The TTW and WTT efficiency are determined. Gaseous hydrogen (H_2) has a WTW efficiency of 25% low heating value, if produced from methane and used in a fuel cell. This efficiency is similar to diesel and electric traction in the UK, US, and California. A reduction of about 19% in CO_2 is achieved when hydrogen gas is used in a fuel cell compared to diesel traction, and a 3% reduction compared to US electricity. The paper shows that a high WTW efficiency reduces the amount of energy needed from the original source and that a reduction in overall emissions is possible. The case of diesel traction demonstrates that a high WTW efficiency does not automatically lead to lower emissions. Hydrogen as an energy carrier to provide power for railway vehicles is a suitable solution on efficiency and emission bases, if fuel cells are used. The WTW efficiency is similar to electric and diesel systems, but the CO_2 emissions are lower than for diesel traction. If electricity is largely produced from high carbon fuels, a reduction of CO_2 is possible through the utilization of hydrogen when produced from natural gas.

Esters and Marinov (2014) analyzed and compare the methods used for calculating emissions of UK rolling stock based on their type and mode of operation. The three modes under comparison were diesel, electric and bi-mode. As well as comparing these three modes of operation, a comparison between Conventional, Freight and High Speed Rail was made. Alternate fuels were considered for diesel and bi-mode locomotives and compared based on their environmental impact. The emissions of trains were studied using three methods presented in Sec. 3. Specifically, the three chosen methods were used to calculate the emissions of each train and a comparison of these methods was made. In the current UK energy climate, diesel trains emit less emissions than electric trains when factoring in mechanical and air resistances, due to domination of high carbon primary source for electricity production. Bi-mode trains have their place in the UK network but with electrification of the network currently in place, this mode of operation will become redundant in the near future. High Speed Rail, although time efficient, releases high emissions due to energy consumption increasing with the square of speed. Alternative fuels, such as biodiesel, should be a consideration for the future of rail, as emissions fall significantly with content of biodiesel in fuel blends.

Gangwar & Sharma (2014) adopted a WTW approach to quantify the emissions from diesel and electric locomotives in India. Results showed that the accumulated carbon footprint of running electric locomotives was higher, as a consequence of using coal as a primary source in electricity production. They suggest that there should be a judicious mix of both tractions to achieve a balance in environmental efficiency, sustainability and equity.

Washing and Pulugurtha (2015) used WTW analysis to combine the energy efficiencies of each component of the energy pathway into a single energy efficiency value. The focus of this paper was on WTW analysis of electric and hydrogen light rail. The inefficiencies of the hydrogen train's power plant and hydrogen production process are apparent in the hydrogen train's WTW efficiency value of 16.6–19.6%. The electric train, due to improved pathway efficiencies, uses substantially less feedstock energy with a WTW efficiency value of 25.3%. While this result is specific to Charlotte, North Carolina, the electric train efficiency is influenced by the main source of electricity production – it is 24.6% in Cleveland, Ohio (with domination of coal) and 50.3% in Portland, Oregon (with domination of hydroelectric power).

The main limitations and issues identified concerning the available literature on WTW analysis in railway passenger transportation, alongside with those addressed in the previous section, are:

- lack of comprehensive WTW evaluation of different railway passenger vehicles, especially powered by alternative energy options, and different driving conditions;
- lack of consistent formulation and comprehensive studies of different energy carriers pathways, especially for alternative fuels, as well as different energy and electricity generation mixes.

Limitations listed first can be addressed by developing detailed vehicles models and simulation tools based on bottom-up methods which would enable identification and analysis of different technological and operational parameters, related to technology improvements, driving conditions and strategies, etc. Additionally, limitations related to WTT stage can potentially be addressed using a formal thermoeconomic analysis, which uses exergy to account for the consumption of primary resources and to allocate it over multiple products (Orsi et al., 2016), where exergy can be defined as “the amount of useful work extractable from a generic system when it is brought to equilibrium with its reference environment through a series of reversible processes in which the system can only interact with such environment” (Moran et al., 2012).

5 Railway Life Cycle Assessments

A Life Cycle Assessment (LCA) is an environmental management tool used to understand and compare how a product or a service is provided from “cradle to grave” – a term used to describe the life cycle of a product or a service from its first derivatives to its end-use (Banar and Özdemir, 2015). The main phases of each LCA are shown in Fig. 2.

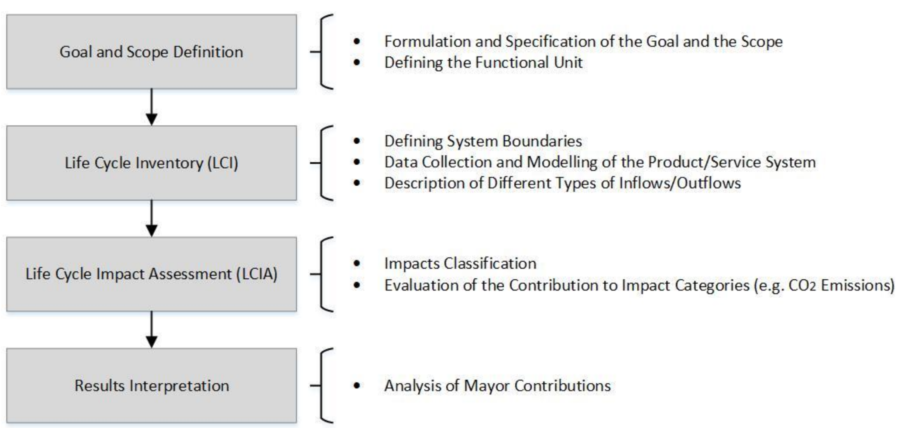

Figure 2: Main phases of a LCA

There are two different methodologies in the literature for LCA, which can also be combined into a hybrid model (Jones, 2017), depending on the goal, scope and constraints of the study:

(i) Process-based LCA – performed by mapping all processes associated with all life cycle phases of the product/service.
(ii) Economic input-output analysis-based (EIO-LCA).

A process-based methodology is performed by mapping all processes associated with all life cycle phases of the project, where inputs (e.g., electricity, steel) and outputs (e.g., air emissions, water discharges) associated with each process are included which enables the total environmental load to be calculated (Jones, 2017). It provides very detailed analysis, but it can require a vast amount of data to include upstream processes (Noori et al. 2013, 2015).

EIO-LCA combines an economic input-output (I-O) model with environmental data so the environmental load of the production of the associated commodities is determined. The I-O model identifies the interdependencies between the different economic sectors and includes the effects of the supply chain. This methodology provides an inclusive and industry-wide analysis allowing for system level comparisons, but can lack the detail of a process-based LCA because it aggregates data to industry sectors (Noori et al. 2013, 2015; Jones, 2017).

The goal and scope definition is the first stage in a LCA study. The significance of this stage is that the decisions made in this phase guide the entire study. Also, functional unit (FU) is defined in this phase. FU is defined as a reference unit for normalization of a quantified performance of a certain product (Guinee et al., 2002), and typically used FUs in railway studies are vehicle kilometer (vkm) or passenger kilometer (pkm) traveled. Several functional units can be used depending on a question that is being informed. Normalization per Vehicle Kilometer Travelled (VKT) is useful for evaluating specific corridor but this does not account passenger carrying capability.

Life cycle inventory (LCI) is one of the most effort consuming stage as it involves the collection, compilation and interpretation of the actual system data in line with the goals and scope of the study and as an input to subsequent life cycle impact assessment stage. Compiling the relevant data for extensive system boundary and collecting it scattered across various sources is usually the major challenge (Shinde et al., 2018).

The Life Cycle Impact Assessment (LCIA) identifies the environmental impacts of LCI results by associating inventory data with potential environmental impact categories (e.g. global warming, acidification, etc.). Several methods and tools are developed for assessing the environmental impacts, such as CML 2001 (University of Leiden, 2001), ReCiPe (Goedkoop et al., 2013), and others.

LCA papers for railway passenger transportation are listed in Table 1, together with the geographical information on the study (country), transport mode considered and system boundaries. Regarding the system boundaries defined, in most cases if the rail infrastructure already exists and the alternative scenarios do not entail developing a new rail network from scratch, the environmental impacts related to the infrastructure are excluded. If the study concerns construction of the new line, such as a high-speed rail line, the infrastructure is then included in the analysis.

Table 1: LCA papers by country and area of contribution

Publication	Country	Transport Mode / Area	System Boundary
Von Rozycki et al. (2003)	Germany	High-speed rail	Infrastructure construction and operation (including buildings); vehicle manufacturing, traction, and maintenance
Castella et al. (2009)	South Korea	High-speed rail	Rail car-bodies raw material production, manufacturing, use, and end-of-life
Stripple and Uppenberg (2010)	Sweden	Rail transportation (passenger and freight)	Infrastructure construction and maintenance (including tunnels, bridges, track foundation and track, stations, freight terminals, signalling system); manufacturing and operation of train carriages
Åkerman (2011)	Sweden	High-speed rail	Infrastructure construction, maintenance, and operation; vehicle manufacturing, maintenance, and use
Chang and Kendall (2011)	USA	High-speed rail	Infrastructure construction (buildings and stations excluded, as well as infrastructure operation and vehicles)
Chester and Horvath (2012)	USA	Passenger transportation (high-speed rail, emerging automobiles and aircraft technology)	Infrastructure construction, operation, maintenance, and insurance; vehicle manufacturing, operation, maintenance, and insurance
Chan et al. (2013)	Canada	Commuter rail system	Vehicles operation; fuel production/electricity generation
Banar and Özdemir (2015)	Turkey	Rail passenger transportation (high-speed rail, conventional rail)	Infrastructure (production and distribution of electrical energy, extraction and production of raw materials, construction, maintenance and operation of lines and waste disposal); rail operation (production and distribution of electrical energy, extraction and production of raw materials, production, maintenance and operation of railway vehicles); and waste disposal
Del Pero et al. (2015)	Italy	Heavy metro	Train material acquisition, manufacturing, use, and end-of-life
de Andrade and D'Agosto (2016)	Brasil	Metro line	Infrastructure construction, and operation; train manufacturing, operation, and maintenance
Dimuola et al. (2016)	Greece	Road and rail transportation (passenger and freight)	Infrastructure construction (road and rail); operation (road and rail)
Jones et al. (2017)	Portugal	High-speed rail	Track construction, operation and maintenance, and disposal; train manufacturing, operation, maintenance, and disposal
Shinde et al. (2018)	India	Suburban rail	Infrastructure construction and maintenance; vehicle manufacturing, maintenance, and operation

Stripple and Uppenberg (2010) developed environmental product declarations (EPD) for newly constructed Bothnia Railway Line in Sweden. Comprehensive life cycle model of the entire railway system was developed. Results showed the greatest contribution to the project's global warming potential (GWP) from the railway infrastructure (93.3%), while the trains operation contribution is just 6.7%, with the main GHG fossil-based CO_2, while emissions of N_2O only give minor contribution. The infrastructure construction stands for the main part of the GHG emissions, with the main source in the production of different materials, while the actual construction work is much smaller. Emissions from the infrastructure and trains operation are very small due to the use of green electric power (the electric power production mix in Sweden in year 2008 was 99.2% hydropower and 0.8% based on biomass fuel).

Akerman (2011) used LCA to research the mitigating climate change effects of a proposed Swedish high-speed rail track and found significant reduction of greenhouse gas emissions because of transportation modes shifting to HSR. The life cycle emissions reductions are found to be 550,000 tons of $CO_{2\text{-eq}}$ per annum by 2025/2030 with almost 60% of this coming from a shift from truck to rail freight and 40% from a shift from air and road travel to high-speed rail travel. However, new railway construction and maintenance may weaken that effect.

Chang and Kendall (2011) performed a process-based LCA study on a greenhouse gas emissions estimation in the construction of the California high-speed rail (CAHSR) infrastructure with specification of several infrastructure types depending on terrain. They found that 80% of the infrastructure emissions resulted from material production, and that tunneling and aerial structures which took only 15% of the route's length, resulted in 60% of the emissions.

Chan et al. (2013) investigated the GHG impact of several alternatives for the commuter rail system in Montreal, Canada. Evaluation of environmental performance and cost of current diesel powered trains against electric powered trains and hydrogen fuel cell system using steam methane reforming (SMR) and wind energy was carried out. They found that electrification, with hydroelectric power, would reduce GHG emissions by more than 98% relative to the current diesel powered trains, while using hydrogen would bring a reduction of 24% or 82% if produced via SMR or via renewable electrolysis, respectively.

Banar and Özdemir (2015) conducted a life cycle assessment and life cycle cost analysis of Turkey's railway transport systems aiming to assess the environmental and economic impact and to serve as guidance for future railways projects to reduce their life-cycle environmental impact in Turkey. The total environmental load of high-speed rail is shared by infrastructure and operations, with percentages of 58% and 42%, respectively. On the other hand, for conventional rail, infrastructure created 39% of the total environmental load, while operations had 61%.

Del Pero et al. (2015) performed a predictive LCA of a heavy metro train investigating on the recyclability/recoverability of the metro vehicles. A sensitivity analysis aimed at defining the variation of environmental impact depending on Vehicle Occupancy (VO) was also carried out. Results showed that the greatest impact results from the operation phase, as well as that there are great possibilities for improvements in this phase.

de Andrade and D'Agosto (2016) assessed the energy used and the emissions produced and avoided in the lifecycle of a new line of the metro network in Rio de Janeiro, built as a requirement for hosting the Olympic Games in 2016. Infrastructure construction, train manufacture, maintenance, infrastructure operation and train operation were considered in the 60-year lifecycle. They concluded that the increase in the renewable energy share in electricity generation and improvements in the production of cement and steel, are the key factors in reducing emissions produced during the life cycle.

Shinde et al. (2018) performed an LCA for the Mumbai Suburban Railway with the objective of developing a comprehensive methodology for environmental evaluation of suburban railway projects in terms of energy consumption and relevant impact categories. The scope of the research comprises the construction and maintenance of railway infrastructure such as tracks, power supply installations, foot over bridges and platforms, in addition to manufacturing, maintenance and the operation phase of Electric Multiple Units (EMUs). The results show that operation phase is the main contributor (87-94%) to the total environmental impact, whereas the contribution of remaining life cycle phases is relatively insignificant (6-13%), mainly due to electricity production from non-renewable sources in India. The material and energy intensive rails entail the major contribution to construction phase (24-57%) and maintenance phase (46-71%),

Based on the existing literature on LCA in railway passenger transportation, main limitations and issues in environmental impact assessment from a life cycle perspective are identified as:

- lack of comprehensive LCA evaluations that include detailed WTW analysis and consumption phase models;
- lack of extensive comparative and sensitivity analyses that assess the effects of different scenarios (e.g. different occupancy rates), as well as technological changes, operational and policy measures;
- lack of elaborate and detailed studies that analyze emissions from the construction/production and end-of-life phases.

Main challenge in performing LCA is the incorporation of detailed emission models from the consumption phase and the WTW pathway, together with addressing the issues and challenges identified in these studies. Although there is an increasing attention on environmental issues regarding construction/production and end-of-life (EoL) phases, the impact of these activities in terms of GHG emissions is still neglected. Initiatives such as the assessment framework proposed by the European association of railway supply industry (UNIFE, 2014) which is to be used on a voluntary basis, represent a good starting point to address this issue.

6 Discussion

Based on the review of the existing research, the main challenge is answering how the available partial assessments can be brought together and, together with filling the identified gaps, allow to conduct a comprehensive LCA which will produce real-world emissions estimations.

Since the total life cycle emissions are directly influenced and dependent on the direct energy consumption and emissions, consumption phase represents the main driver of the total life cycle emissions from the rail passenger service. An effective approach could be the development of detailed direct emissions estimation models and setting them as the central and starting point in future LCA studies. Extending the existing consumption phase models by incorporating real-life conditions that influence consumption and emissions, mentioned in Sec. 3, would serve as the main input for a wider-scope WTW analysis, and subsequent LCA. Real direct measurements can be a valuable input in microscopic bottom-up models development, calibration and validation. The development of mesoscopic models which combine the preciseness of microscopic models while requiring only little more information than the rough estimating macroscopic top-down models could help in overcoming the limitations such as high complexity and data availability. An example of such models can be found in Kirschstein and Meisel (2015) for intermodal rail/road transport.

Common approach in assessing the total WTW emissions is by multiplying the total energy consumption with the WTW emission coefficients, which usually represent adopted average values and may lead to incorrect and biased estimations. Since the real value of this coefficient is highly influenced and directly dependent on the actual energy carrier pathway, formulating and determining all the processes within the different energy carrier pathways – together with associated energy consumption and emissions – is of great importance. Elements and aspects such as primary energy source extraction, energy carrier production and distribution, electricity generation mix should explicitly be taken into account. Integrated with an effective bottom-up vehicle models, which are easy to calibrate for different technological and operational parameters and which would enable assessment of direct energy consumption and emissions, it would allow obtaining factual WTW emissions and generate important input for a subsequent LCA.

Incorporating detailed consumption and WTW models into LCA could help not only in actual emissions assessment, but also in identifying the effects of different technological changes, as well as operational and policy measures. Contrary to the common approximate top-down estimation approaches found in LCA studies, it would potentially enable more consistent estimations from the vehicles/infrastructure operation phase, especially important in case of comparing different options and measures.

Another issue identified in LCA studies is the lack of elaborate and detailed studies that analyze emissions from the construction/production and EoL phases. Although some of the train manufacturers started producing the environmental product declarations (EPDs) for their trains, this number is still relatively small. These EPDs could be valuable source of information for the LCA studies, especially regarding the materials usage, energy consumption and environmental impact from the production phase. Concerning the EoL phase, contrary to the low environmental impact of railway transport with respect to other transport modes, the amount of EoL waste generated by rolling stock in relation to the number of road vehicles is significant. The study by Delogu et al. (2017) gave an overview of EoL railway vehicles management issues and analyzed the recoverability/recyclability rate for three types of railway vehicles (electric metro, diesel commuter train and high-speed electric train). As stated in this study, the disposal of a railway passenger vehicle in terms of weight of the obtained waste corresponds to 36-42 road passenger vehicles, although there is no consideration of the comparative capacity of the vehicles (railway car in automobile equivalents) or the comparative service life of road and railway vehicles, both of which are important considerations.

7 Conclusions and Future Research Directions

This paper presented a review of existing research on life cycle emissions from railway passenger services. Studies and approaches focused on the direct emissions from the consumption phase are presented first, followed by wider-scope WTW analyses which observe energy carrier life cycle, and LCA studies which encompass infrastructure and/or vehicles life cycles and associated emissions. A comprehensive analysis of existing models enabled identifying the research gaps and addressing the main issues and challenges in assessing the overall impact in terms of GHG emissions. Additionally, possibilities in addressing the limitations and filling the identified gaps are given.

Future research will include development of a framework for life cycle emissions estimation and prediction, observing both conventional and alternative energy options for railway passenger transport. First, detailed pathways will be determined, including processes related to: primary resource recovery, extraction and transportation to the construction/production facilities; activities in construction/production; distribution of the energy carrier to the vehicles; operation and maintenance; and end-of-life activities (recycling, reuse and disposal). Environmental impacts from all processes and sub-processes will be evaluated by developing and employing bottom-up methods. Results will be validated through real-life measurements and comparison with the results of other world-wide studies. Special attention will be given to the efficiency of the system elements. Sensitivity analysis will be carried out with the aim of assessing the possibilities in improving the environmental impact of the rail passenger service, and will include technological, operational and policy measures.

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