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Life Cycle Assessment of a heavy metro train

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ABSTRACT

The railway system represents one of the most resource-efficient answer to the ever-growing demand for transport service. Development trends for the following years project substantial increase in this sector. To date, environmental effects caused by railway transport services have been rarely inspected systematically and existing studies focus on single typologies of environmental aspects, like energy consumption and air emissions. The article presents a predictive Life Cycle Assessment (LCA) of a heavy metro train that will operate in the urban area of Rome. A predictive analysis on recyclability/recoverability at the end of life has also been performed according to the ISO 22628. The LCA inventory captures the whole vehicle Life-Cycle (LC) subdivided in four stages: Material acquisition, Manufacturing, Use and End of life. In comparison with existing studies, this work examines a broader range of impacts to human and ecosystems health using primary data supplied by vehicle manufacturers whenever possible to reduce the uncertainty of results. Results show that Use is largely the most influential stage for the majority of the considered impact categories. This fact is due to the energy intensity of Use stage since it accounts for almost the entire amount (98.3%) of electricity consumed during vehicle LC. Material acquisition is the second most influential stage based on resource consumption and emissions during extraction of Iron and Bauxite: vehicle parts that mainly contribute to impacts of Material acquisition are body structure and bogies. The impacts associated with Manufacturing and End of life are low compared to the other stages. The projected recyclability and recoverability rates at the end of life stage are respectively 87.4% and 92.1%. A sensitivity analysis of the LCA results stresses the influence of vehicle occupancy on the electricity consumption during operation and the overall LCIA results. In light of LCA results, major improvement potential is identified in the reduction of electricity consumption during use stage, primarily due to Traction and Heating systems. The key recommendations for future design strategies are the decrease of vehicle mass by the application of lightweight materials for metro construction and the improvement of efficiency of the Heating system.

1. Introduction

Our global society is strongly dependent on transportation with development trends indicating a substantial growth in this sector over the coming decades (Hawkins at al., 2012). The transportation industry (including all the transport modes, from air to surface traffic) is currently the second largest contributor to anthropogenic GreenHouse Gas (GHG) emissions within the European Union. Around 20% of these emissions are generated by road transportation, including both private/public and passenger/freight vehicles (Witik et al., 2011). Globally, light-duty vehicles account for approximately 10% of total energy use and GHG emissions (Solomon et al., 2007). According to a study commissioned by the World Business Council for Sustainable Development (2004), light-duty vehicles ownership could increase from roughly 700 million to 2 billion over the period 2000–2050. These patterns forecast a dramatic increase in gasoline and diesel demand that will have implications on energy security, climate change and urban air quality (Hawkins at al., 2012).

In light of these considerations, environmental analyses and eco-design solutions have been applied in depth to all the Life-Cycle (LC) stages of automotive vehicles and components (Berzi et al., 2013; Cappelli et al., 2007; Mayyas et al., 2012). In this context, many Life Cycle Assessments (LCAs) (Chanaron, 2007; Finnveden et al., 2009; ISO 14040, 2006; ISO 14044, 2006) of both conventional (Finkbeiner et al., 2006; Schmidt et al., 2004; Spielmann and Althaus, 2006)) and innovative (Alves et al., 2010;

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Nomenclature

AB	AnsaldoBreda
ADP_e	Abiotic Depletion Potential elements
ADP_f	Abiotic Depletion Potential fossil
AP	Acidification Potential
CED	Cumulative Energy Demand
EoL	End of Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
E_{RR}	Electricity per Round Route
FAETP	Fresh water Aquatic Eco-Toxicity Potential
FU	Functional Unit
GHG	GreenHouse Gas
GWP	Global Warming Potential
HSR	High Speed Rail
HTP	Human Toxicity Potential
HVAC	Heat Ventilation Air Conditioning
ICE	Inter City Express
LC	Life Cycle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MAETP	Marine Aquatic Eco-Toxicity Potential
MIPS	Material Input Per Service
MS	Material Sheet
ODP	Ozone Depletion Potential
OEMs	Original Equipment Manufacturers
PCR	Product Category Rule
PEE	Potential Environmental Effect
PG	Product Group
PKT	Passenger Kilometres Travelled
POCP	Photochemical Ozone Creation Potential
PU	Process Unit
SI	Supporting Information
TETP	Terrestrial Eco-Toxicity Potential
TS	Transport Sheet
VKT	Vehicle Kilometres Travelled
VO	Vehicle Occupancy

Du JD et al., 2010; Duflou et al., 2009; Luz et al., 2010; Mayyas et al., 2011; Vinodh and Jayakrishna, 2011; Zah et al., 2006) alternatives for personal transportation have been performed to understand how the associated impacts can be reduced. However, less interest has been paid to the transportation by railway. Some studies limit their field of investigation to the railway sector, others make a comparison between railway and different types of transportation emphasising the influence that they have on specific areas. The results for the multi-mode studies, particularly when considering the impact to Global Warming, suggest railways can be a more environmentally preferred mode of transportation when compared with other modes such as roadways.

Stodolsky et al. (1998) compared the environmental profile of rail and on-road modes for the transportation of freight. Energy use and emissions were examined taking into account the whole vehicle LC. Using secondary data for energy use and emissions, the paper identifies the use stage as the greatest contributor to environmental impacts for both modes.

Rozycki et al. (2003) conducted a screening LCA of the German high-speed passenger train ICE. Data collection was based on inventory values supplied by railway experts and internal documents of rail operators. In the study resource consumption caused by traction, manufacturing and maintenance of the train as well as construction and operation of the supporting infrastructures and buildings were considered. As reference for the impact assessment, the 100-person-kilometre unit was as the functional unit, with impact categories of Cumulative Energy Demand (CED), cumulative Material Input Per Service unit (MIPS) and CO_2 emissions. The results state that operation represents the greatest contribution to impacts: use stage contribution is 64%, 31% and 70% respectively to CED, MIPS and CO_2 emissions, these latter being dominated by energy-related processes.

Struckl and Wimmer (2007) conducted a cradle-to-grave, screening-level LCA of a light metro train produced by SIEMENS for operation in the Oslo area. Their assessment included a range of categories describing impacts to health, the environment and resource use. A contribution analysis by stage of the Global Warming impacts identifies the use as the most relevant, followed by material acquisition and manufacturing. A detailed analysis of contributions coming from single vehicle systems denotes that traction and heating have the greatest influence on the impact caused by the use stage. The impacts during material acquisition and manufacturing are predominantly associated with the car body and bogies. To date the work of Struckl and Wimmer is the only published scientific paper regarding LCA of a metro train.

A comparative LC energy and emissions inventory for three U.S. metropolitan regions was presented by Chester et al. (2009). The study considered different transport modes (automobile, diesel rail, electric rail and ferry service) and captured both vehicle operational (direct fuel and electricity consumption) and non-operational (vehicle manufacturing, roadway maintenance, infrastructure operation and material production) components. Life cycle inventories for the three regions were developed using surveys and existing inventory datasets for the various modes of transportation. Functional units based on either the Passenger Kilometres Travelled (PKT) and the Vehicle Kilometres Travelled (VKT) were used as the basis for comparison. The automobiles are identified as the dominant source of impact, accounting for 86–96% of the regional energy use and emissions. The paper shows also an interesting interpretation of the results by disaggregation of transportation modes between off-peak and peak travel time: automobile involves significant emissions to system-wide emissions but the contribution of larger shares on public transit and its improved per-PKT performance can offset this.

Another comparative study is the one performed by Chester and Horvath (2009) who evaluated the LC energy and GHG emissions for different transportation typologies in the US (buses, trains, and airplanes), including the supply chain and production of vehicles, infrastructures and fuel. Secondary data sources from publicly available literature were used to model the selected transportation modes. The results, calculated with respect to the Passenger Kilometres Travelled (PKT) indicate both energy consumption and GHG emissions are better for commuter and light rail systems when compared with buses (urban diesel) and aircraft (small, midsize and large). A contribution analysis by stage determines the dominant share of both energy use and emissions for road and air modes is associated with operational components, while these values for railways are more strongly influenced by non-operational components. According to Chester et al. (2009), sensitivity analysis based on variation of Vehicle Occupancy (VO) finds the relative performance of modes is highly dependent on the number of passengers.