# Developing a Framework for Life Cycle Assessment of Green Transportation Infrastructure (Railway and Super pavements)

Manouchehr Shokri [1*], Rose Mankaa [1] and Marzia Traverso[1]

[1]Institute of Sustainability in Civil Engineering (INaB), RWTH Aachen University, Germany

**Abstract.** As well known, the transportation industry and its related infrastructure including railway and roads, require very high construction costs. In addition, the excessive use of natural resources and energy for related construction and maintenance has highlighted the need for adapting purposeful planning with regards to sustainability related impacts. In transportation infrastructure, the focus should be to minimize energy consumption, related Greenhouse Gas emissions and other environmental impacts over their entire life cycle. In this study, a new design of substructure with a layer of recycled Polypropylene (PP) is presented and compared with scenarios using virgin PP and conventional ballast. A model was developed that can adequately evaluate the resource use and environmental effects of various use scenarios of Geosynthetic (recycled Polypropylene) materials in rail construction layers in comparison to primary raw material. The model takes into consideration technical properties investigated through finite element simulations to decouple increase technical performance from environmental impacts. The outcome of Life Cycle Assessment (LCA) indicates that the recycled PP scenario causes the lowest environmental impact for a service life of 100 years. On the other hand, the Finite Element (FE) results showed that using reinforced geosynthetics between ballasted layer has better mechanical performance than the conventional ballast track railway.

## 1 Introduction

The development of Circular Economy (CE) requires industrial sectors to cooperate in the reuse and recycling of by-products to attain "zero waste" goal. Therefore, throughout the world, there are many innovative sustainable activities that have been undertaken to improve the performance of infrastructure products and decrease its environmental impacts. Meanwhile, 25-30% of all generated waste in the EU is Construction and Demolition (C&D) waste, which is among the most voluminous and heaviest waste streams generated. The billions of C&D wastes produced each year have intensified severe environmental concerns

---

*Corresponding author: manouchehr.shokri@inab.rwth-aachen.de

and reinforced the need for more efficient waste management in the construction sector [1]. Specifically, large amounts of C&D waste across the EU and their extreme potential for valorization have led the EU to categorize them as a priority waste stream [2]. Incorporating sustainable practices, including the use of alternative, environmentally friendly materials and reuse of C&D wastes can greatly lead to enhanced overall sustainable development [3]. Approximately 40% of natural aggregates are utilized in unrestricted layers of transportation infrastructures of Europe, indicating the high dependency of natural aggregates in geotechnical applications and the incorporation of recycled aggregates can greatly contribute to preserving the environment [4].

The last few years of the 21st century have seen significant advances in rail infrastructure and the result is that speed increases in both freight and passenger services up to 160 km/h and 350 km/h, respectively [5,6]. The railway substructure transmits these speeds and must be sufficiently resistant and strong to support heavy loads throughout operation. Weak foundation soil can be one of the problems of railways construction; and geosynthetics as a structural reinforcement can lead to the durability of railway structure. Geotextiles and geogrids are mainly the prevalent geosynthetics used in a foundation. These smooth structures are commonly used for reinforcement of soils and mechanical stabilization of the subsoil [7, 8]. Accordingly, recognizing current concern about climate and environment, the railway system and substructure can be regarded as the key factors in decreasing noise and air pollutants. Therefore, the possible effect of construction and its maintenance process should be evaluated; and "Life Cycle Assessment (LCA)" of products, as an internationally recognized methodology, can be used for this purpose. This study introduces a new design of substructure with a layer of recycled PP and a comparative LCA is implemented using virgin PP and conventional ballast.

The Finite Element Method (FEM) is an approved technique for solving various engineering problems. The simulation study based on the finite element method is carried out by the ABAQUES software for railway structure. This software analyzes physical and nonlinear issues of solids. Different elements of railway structure are regarded as the targets of simulation section and this research investigates the simulation analysis results. However, with regards to unit function analysis of the railway, modeling is initially carried out using FEM for layers not using geosynthetics and its analysis is carried out for displacement, stress and strain. Then, the previous section, displacement, stress and strain analyses are carried out for reinforced railway track and eventually the model is compared with the previous unit function.

As well known, the transportation industry and its related infrastructures including the railway, roads, and bridges, require very high construction costs. The excessive use of natural resources and energy for related construction, maintenance and its environmental impact has enhanced the need for adapting purposeful planning. Secondary and recycled materials can be quite helpful in this regard from all perspectives of life cycle assessment. Previous research related to using recycled material was mostly for technical and mechanical evaluation, as has been done on the railway infrastructure industry. In this study, a new design of substructure with a layer of geogrid from recycled PP materials is employed between ballasted layers. As a first step, the mechanical behavior of this substructure is evaluated by finite element simulation. Next for environmental impacts, the LCA of the substructure is evaluated. Studies on this section are essential because of the high requirements to reduce substantial costs of building infrastructure. Also, the research with the diagnosis of infrastructure parts should be conducted to diminish performance costs and increase security.

## 2 Material and Method

### 2.1 Substructure design

In this research area conventional and reinforced layers of recycled, original PP as geosynthetic materials are used between ballasted layers inside the railway track substructure. It is well known that geosynthetics are typically made from petrochemical-based polymers (plastics), Polypropylene (PP) is the most frequently used material in connection with Geosynthetics. The necessity to enhance railway durability and driver comfort has resulted in research on the use of reinforcements for these types of railway substructures. When the subgrade is weak, a geosynthetic (geogrid and/or geotextile) layer can be situated over the subgrade to reinforce the track. In this study, firstly, the mechanical effect of the PP as a reinforced layer inside the substructure is investigated by Finite Element simulation.

In this study, firstly, the mechanical effect of the PP as a reinforced layer inside the substructure is investigated by Finite Element simulation. FEM is implemented to analyze the dynamic axel load response of railway track components (conventional and new design). The support method utilized during the experiment is substituted by the numerical model using perfect boundary conditions. The rotational speed of the roller that simulates the vehicle speed, and the pressure of a dynamic or static roller on the rail are present. The system of equations is solved in each step, and the load is incrementally applied to determine the change in stresses, displacements and deformations. By eliminating appropriate degrees of freedom, support conditions are determined, thus inhibiting the model from deviating in certain directions. The grid in individual surface elements has a different size in the case of solid models. Contact points between individual elements of the railway surface are determined to adequately conduct the simulation computations. Figure 1 shows boundary condition and simulated model in this study. The rail and wheel contact in the model is specified as the interaction between surfaces created on the head of the rail and on the wheel.
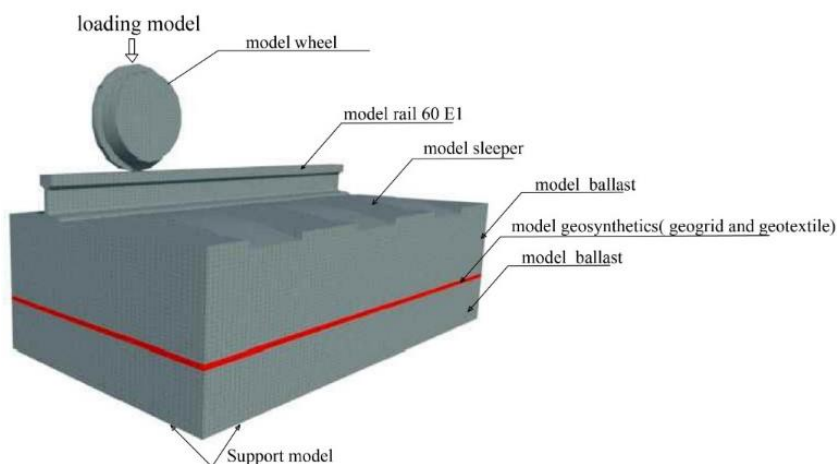


**Fig. 1.** Boundary condition and load for model with geosynthetic reinforcement

## 2.2 Life cycle assessment methodology

An effective method is provided by the LCA methodology to find out the possible environmental impacts of every process or product through its life cycle [9.10]. The application of the LCA is employed in this study to examine various railway track pavement solutions according to ISO 14040 series for the modern railway lines. The process includes the four steps of LCA: definition of the goal and scope, inventory analysis, impact assessment, and interpretation of the outcomes. Particularly in the present analysis, the CML method is selected for the life cycle impact assessment (LCIA).

The main goal of the LCA method is comparing two types of railway track system for twin railway track substructure designs, with reinforced geogrid layer (Original and recycled PP) and conventional ballasted railway track. In addition to develop transparent LCA framework for railway track system components could be used for decision making support. Consequently, the outcomes of these different designs are compared with each other. The final results offer valuable insights into the environmental impacts during the operation, construction and maintenance of railway tracks that can be employed by managers and engineers.

The LCA technique is performed following a "cradle-to-grave" perspective including raw material acquisition and production, construction (transportation of processed material to construction site, machinery, and operations), use including maintenance (minor and regular, e.g., ballast tamping and component renewal), and finally the dismantlement operations, landfilling, disposal, and recycling. The LCA Model and system boundaries of the case study are presented in Figure 2. The environmental impacts of the design are studied by the LCA methodology. LCA according to ISO 14040 & 14044 standards is carried out and the outcome of the LCA is used to develop the decision support model specific to the transportation infrastructure sector.
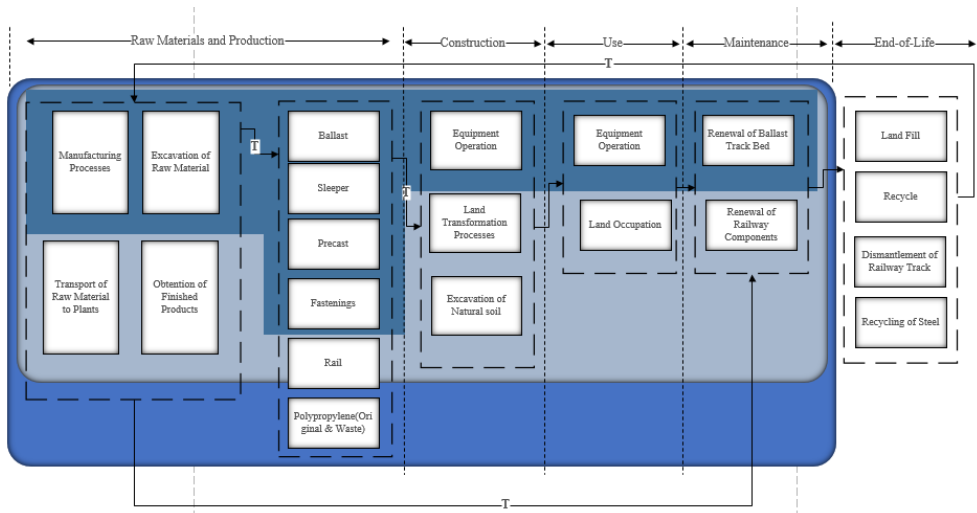


**Fig. 2.** LCA Proposed methodology of Railway track construction for this research system boundary area

## 3 Results

The results of the simulation step by finite element method are presented in this section. Figures 3(a) and 3(b) indicate the diagrams for the original substructure and the substructure with the geogrid layer, respectively. The diagrams show the contours of deformations (deflections) of the model elements and Huber–Misess replacement deformation. It can be noticed that using the geogrid layer inside the substructure leads to more even deformations and distribution of stresses.
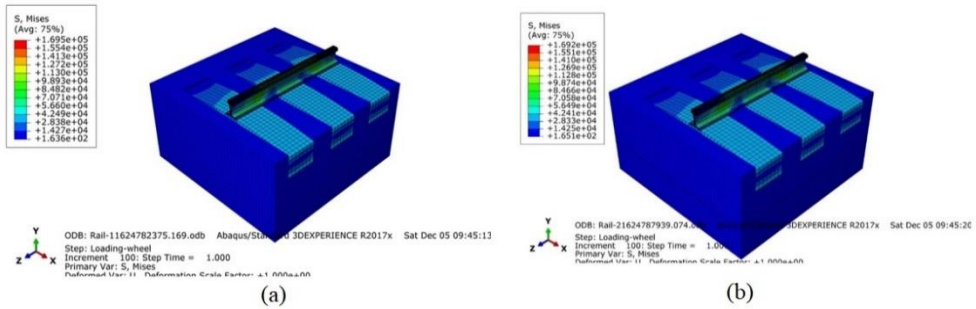


**Fig. 3. (a) and (b)**: Contours of S, Mises stress for classic and reinforced scenario

For a better understanding of elements, Figures 4 (a) and 4 (b) provides the results of elements in the conventional track railway and reinforced ballast, respectively. Firstly, it is observed that employing the geogrid layer leads to lower displacement and deformation on the railway surface compared to the classic substructure. Consequently, this difference has enough potential for an increase in the fatigue life which is affected by cyclic stresses. Secondly, the geogrid layer inside the substructure causes lower deformation that shows the resistance to applied loads and displacements. Overall, using the geogrid material has noticeable benefits for both of the substructure and rail system when this layer provides a longer useful life and reduction in maintenance costs.
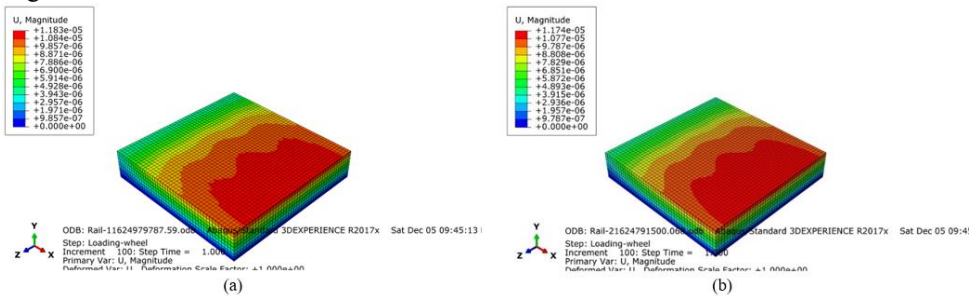


**Fig. 4. (a) and (b)**: Contours of Elastic deformation (U, Magnitude) of for classic and reinforced ballast of railway track system(bottom)

The recycled PP reinforced scenario leads to lowest emissions for raw material acquisition and production and for the whole life cycle. The virgin PP reinforced scenario is the worst option considering $CO_2$ emissions and energy consumption regardless of its service life, primarily because of its reinforced layer. The ballast beds of all scenarios contribute to high $CO_2$ emissions because of the needed ballast for their construction, however, virgin reinforced PP and conventional ballast scenarios have higher shares compared to the recycled PP scenario (Fig 5(a) and 5(b)).
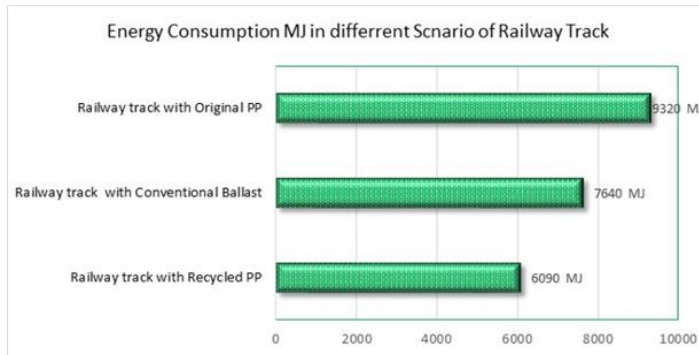
(a)
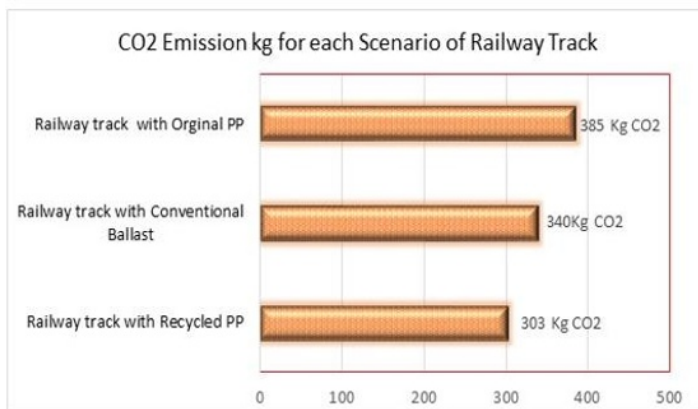


(b)

**Fig. 5. (a) and (b):** Energy consumption and $CO_2$ emission in different scenario of railway track

## 4 Conclusion

This study evaluated the potential of employing a layer of recycled PP as geogrid material in railway track substructure. The mechanical impacts of the layers were assessed by the finite element simulation and results showed significant advantages, such as longer useful life and reduction stress, deformation, displacement and in maintenance costs for both rail system and substructure. Regarding results gained by the LCA approach for a service life of 100 years, the substructure with the recycled PP layer was often the best solution in terms of environmental impacts. This scenario showed important potential for reduction in $CO_2$ emissions and energy consumptions compared to others. Also, the global warming potential of the scenario indicated that most of the emissions are associated with the production and use phases including maintenance. The model developed aims decision making on material resource options to improve mechanical and technical performance while keeping environmental and economic impacts low.

# References

1. Commission E. Roadmap to a resource efficient Europe. COM (2011). 2011;571.

2. Spišáková M, Mésároš P, Mandičák T. Construction Waste Audit in the Framework of Sustainable Waste Management in Construction Projects—Case Study. Buildings. 2021;11(2):61.

3. Trott CD, Weinberg AE, Sample McMeeking LB. Prefiguring sustainability through participatory action research experiences for undergraduates: Reflections and recommendations for student development. Sustainability. 2018;10(9):3332.

4. Ciampa D, Cioffi R, Colangelo F, Diomedi M, Farina I, Olita S. Use of unbound materials for sustainable road infrastructures. Applied Sciences. 2020;10(10):3465.

5. Mikulski J, Gorzelak K. Conception of modernization of a line section example in the context of a fast railway connection. Archives of Transport. 2017;44.

6. Szeląg A. Electrical power infrastructure for modern rolling stock with regard to the railway in Poland. Archives of transport. 2017.

7. Kim D, Ha S. Effects of particle size on the shear behavior of coarse grained soils reinforced with geogrid. Materials. 2014;7(2):963-79.

8. Leonardi G, Lo Bosco D, Palamara R, Suraci F. Finite element analysis of geogrid-stabilized unpaved roads. Sustainability. 2020;12(5):1929.

9. Tokede OO, Whittaker A, Mankaa R, Traverso M, editors. Life cycle assessment of asphalt variants in infrastructures: The case of lignin in Australian road pavements. Structures; 2020: Elsevier.

10. Valdivia S, Ugaya CM, Hildenbrand J, Traverso M, Mazijn B, Sonnemann G. A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio+ 20. The International Journal of Life Cycle Assessment. 2013;18(9):1673-85.