EXAMINATION AND OPTIMIZATION OF THE ECOLOGICAL FOOTPRINT OF EMBEDDED RAIL STRUCTURES

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Abstract In urban planning practice, there has been a growing trend towards the displacement of car traffic, thereby reducing traffic congestion and air pollution, creating the foundations of a healthier, more livable urban environment. In the Hungarian cities, large-scale investments have recently been carried out or are being planned. Most of the investments focused the modernization and renovation of existing line sections, but there are also examples of new lines being built. Due to the increasing demands placed on rail transport (reduction of noise and vibration loads, as well as of life cycle costs), the use of embedded superstructures is gaining ground in Hungary as well. These superstructures are excellent from a technical point of view and have a lower environmental impact in terms of noise and vibration, but the cost savings and ecological footprint (EF) reductions vary between designs. The aim of our research is to explore how the social and economic sustainability development goals of rail transport infrastructure development can be achieved with the least environmental impact. The use of the EF indicator can also help corporate and policy makers to select and support the right construction technology.

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1 Introduction

One of the greatest challenges of the 21st century, while maintaining the continuous development of society, is the protection of the environment, especially including the achievement of climate targets (Skala, 2022). A globalized, industrialized world requires us to maintain, expand and modernize both passenger and freight transport in our cities and countries, as well as between countries, in response to ever-changing demands. Transport concerns are linked to five objectives among the 17 SDGs: target 3.6, 7.3, 9.1, 11.2 12.c (Brussel et al. 2019). In this study, we focus primarily on target 9.1. In the EU, increased attention is being paid to the development of rail and public transport as opposed to individual transport. The construction and operation of transport networks generates significant CO_2 emissions, which do not entail the emissions of the transport vehicles themselves. During construction and operation, emissions are primarily generated by the production, transport, and installation of materials. In this article, we compare two possible versions of so-called embedded track structures, which are frequently found in the tramway network of large cities, in terms of technical parameters and ecological footprint (EF).

2 Literature Review

The reason for selecting the carbon footprint as the ecological footprint indicator for our research was that it is one of the most widely used physical metric (Lin et al., 2018; Wackernagel et al., 2019). The Global Footprint Network (GFN) conceptualizes the EF indicator as comprising five land use categories, of which we only considered the ecological footprint from carbon emissions. In 2010, Chambers et al. (2010) developed the principles for the EF calculations used, which were further developed by Wackernagel and Beyers in 2019. Its applications therefore also include measuring material use in construction (McBain et al., 2018; Szigeti et al., 2023). There are some examples of ecological footprint calculations of transport network construction (de Bortoli, 2020; Gassner et al., 2018; Lv et al., 2021) in the literature, but the comparison of superstructural variants is a novelty of our research.

3 Methodology

3.1 Technical analysis of two tramway tracks structures

The two superstructure designs shown in Figure 1 are the subject of our comparative analysis. The technical solutions presented comply with the regulations in force for the Budapest Transport Company's line network. From a technical point of view, they can be considered equivalent, since both designs are dimensioned for the same load and their useful life is also considered to be the same, since the tested rails can be kept in the track up to the same wear value. The left side of the figure shows the structure with a B3 block rail and the right side with a 59Ri2 rail. The typical differences between the two variants are attributable to the height of the rail system used, so the block rail design results in a more economical structure. In the figure, the rails are shown in grey, the embedding material in red, the material-saving PVC tubes in blue and the reinforced concrete track slab in green. It is assumed that the structure of the load-bearing layer under the slab is the same in both cases, so that the lower plane of the slab (top of subgrade) is 170 mm deeper in the 59Ri2 rail structure, which requires additional excavation work.

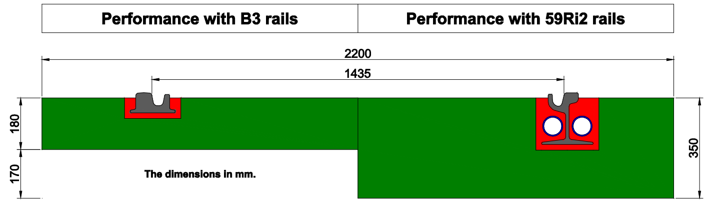

Figure 1: The performance of the investigated structures

Source: Authors' own illustration

3.2 Determination of the typical CO2 emissions of the presented technical solutions

The CO_2 emissions of the main components of the technical solutions presented in Chapter 3.1 (e.g. the embedding material) are considered from two perspectives. The first aspect is the so-called intrinsic emissions of the component material, while the second aspect is the emissions from the transport of the material. The CO_2 emissions from the installation are not addressed in this article, as the technological possibilities are manifold and would increase the number of variations to be investigated beyond the scope of this paper. Another reason for simplification is that, since we are making a comparison, we are interested in the difference in CO_2 emissions between the two variants, which would not change significantly assuming the same construction method. However, if the difference in emissions between the technologies is to be considered, it is of course possible to quantify it. For similar reasons, the structure of the load-bearing layer under the subgrade is also not considered. In our analysis, the total useful lifetime emissions are differentiated according to the assumed useful lifetime of each component and expressed in kgCO_2/track meter/year.

In order to perform the comparative analysis, the five components shown in the following subsections were examined in detail. The specific CO_2 emissions for each material were all considered according to the Inventory of Carbon and Energy Database (ICE) v3.0. The first step in the study was to determine the mass of rail material per 1 m of track for both test cases. This was 109.22 kg/track meter for B3 rails and 116.28 kg/track meter for 59Ri2 rails. Based on ICE database v3.0, the specific value of CO_2 emissions is 1.27 kgCO_2/kg (structural steel). Taking this value into account, the CO_2 emissions of installed rail steel are 138.7 kg/track meter for B3 rails and 147.7 kg/ track meter for 59Ri2 rails.

In determining the amount of elastic embedding material, it was assumed that the thickness of the bottom layer of embedding compound used was a uniform 20 mm. Substituting this value into the formulae defined by Zoltán Major for average cross-sectional geometries of elastic embedding, the specific volume of the embedding material per 1 m of track was calculated. In the case of the 59Ri2 rail, the placement of 2 material-saving PVC tubes with a diameter of 70 mm each was also considered. The specific volume is 16,22 l/track meter for rail B3 and 52,61 l/track meter for rail 59Ri2. As different materials from several manufacturers may be technically suitable for use in the track structure as elastic embedding, an average density value of 0.9 kg/l was considered for the embedding material. The specific weight calculated on this basis is 14.6 kg/track meter for the B3 rail and 47.3 kg/track meter for the 59Ri2 rail. The specific value of CO_2 emissions based on ICE V3.0 is 4.84 kg CO_2/kg (flexible polyurethane foam). Taking this value into account, the specific CO_2 emissions for the installed elastic embedding material are 70.7 kg/track meter for the B3 rail and 229.2 kg/track meter for the 59Ri2 rail. Since the quantity of PVC tubes installed is secondarily small compared to the volume of the other components, the CO_2 emissions from the PVC tubes are not considered in our analysis.

The load-bearing track slab consists of two components: concrete and a reinforcing steel frame. As a good approximation, the amount of reinforcing steel is calculated as 3% of the specific volume of the track slab. The specific volume of the concrete slab was first determined from its geometrical dimensions to calculate its own emission. Assuming a panel width of 2200 mm, the specific volume of the slab was calculated to be 0.396 m^3/track meter for a 180 mm thick slab and B3 rail, and 0.770 m^3/m for a 350 mm thick slab and 59Ri2 rail. In our calculations, the rail ducts have been omitted as an approximation for reasons of simplification. For concrete, a density of 2500 kg/m m^3 was assumed, at 97% of the volume. Thus, the specific mass of the concrete for the B3 rail is 0.96 t/ track meter, while for the 59Ri2 rail it is 1.87 t/track meter. Based on ICE V3.0, the specific value of CO_2 emissions is 0.132 kg CO_2/kg (precast concrete pavement). Taking this value into account, the CO_2 emissions for the installed concrete material are 130.7 kg/track meter for the B3 rail and 254.1 kg/track meter for the 59Ri2 rail. The mass of the reinforcing steel installed, with the previous simplifications, is 93.2 kg/track meter for rail B3 and 181.3 kg/track meter for rail 59Ri2. Based on ICE V3.0, the specific value of CO_2 emissions is 1.99 kg CO_2/kg (reinforcing steel). Taking this value into account, the CO_2 emissions for the installed concrete material are 185.6 kg/track meter for the B3 rail and 360.9 kg/track meter for the 59Ri2 rail.

For the calculation of the subsoil's intrinsic emission, we only consider the excess soil excavation due to the difference in thickness of the two track slabs, which is 170 mm for 59Ri2 rails. We do not consider the soil excavation required to construct the load-bearing layer structure underneath the track slab. For 59Ri2 rails, while considering the required additional track slab thickness of 170 mm and a width of 2200 mm, the additional excavation required is 0,374 m^3/track meter. The density of the soil was considered at 2000 kg/m^3. The mass of the excavated soil is 748 kg/track meter. Based on ICE V3.0, the specific value of CO_2 emissions is 0.024 kgCO_2/kg (compacted soil). Taking this value into account, the CO_2 emission is 17.95 kg/track meter for 59Ri2 rails. For rail B3, an excess of 0 mm can be considered, resulting in CO_2 emissions of 0.0 kg/track meter.

4 Results

To determine the CO_2 value from the transport of each component, the specific masses per 1 track meter as defined in Chapter 3.2. The data were used and results summarized in Table 1.

Table 1: Transport data

Component	Transport distance [km]*	Transport method*	gCO_2/tkm**	B3 rail $kgCO_2/t.m$	59Ri2 rail $kgCO_2/t. m.$
Rail	500	railway	26.7	1.458	1.552
Embedding m.	500	road (solo truck, >26t)	199.3	1.455	4.718
Track slab	250	road (solo truck, >26t)	199.3	47.847	93.036
Subsoil	50	road (solo truck, >26t)	199.3	0.000	7.450

Source: *: author's own assumption, **: Treibhausgasemissionen durch die Schieninfrastruktur und Schienenfahrzeuge in Deutschland

3.3 Calculation of the specific CO_2 emissions for the variants

The values per structure determined in Chapter 3 have been weighted by the estimated useful lifetime of each component to be able to consider the lifetime specific CO_2 emissions. Our results are summarized in Tables 2 and 3. The estimated useful lifetimes are our own assumptions.

Table 2: CO_2 emissions weighted by the estimated useful life of the component for B3 rails

Component	Material	Transport	ΣCO_2	Useful life	Specific value
	kgCO2/track m	$kgCO_2$/track m	$kgCO_2$/track m	year	kgCO2/track m/year
Rail	138.7	1.458	140.158	15	9.344
Embedding m.	70.7	1.455	72.155	15	4.810
Track slab	354.5	47.847	402.347	60	6.706
Subsoil	0	0	0	60	0.000
				Σ	**20.860**

Source: Authors' research

Table 3: CO_2 emissions weighted by the estimated useful life of the component for 59Ri2 rails

Component	Material	Transport	ΣCO_2	Useful life	Specific value
	kgCO2/track m	$kgCO_2$/track m	$kgCO_2$/track m	year	kgCO2/track m/year
Rail	147.7	1.552	149.252	15	9.950
Embedding m.	229.2	4.718	233.918	15	15.595
Track slab	689.4	93.036	782.436	60	13.041
Subsoil	17.95	7.450	25.4	60	0.423
				Σ	**39.009**

Source: Authors' research

Based on the results of Tables 2 and 3, it is evident that when optimizing the same track structure types, it is possible to significantly reduce CO_2 emissions by selecting the appropriate superstructure variant. If the total CO_2 emissions of the assumed track structures over a given

analysis period is to be investigated. For our investigation, the analysis period was expediently set equal to the maximum useful life of 60 years.

The ecological footprint, expressed in global hectares (gha), can be defined as the product of CO_2 emissions in tons multiplied by the Footprint Intensity of Carbon published by the Global Footprint Network (Lin et al., 2018) (Table 4).

Table 4: Ecological footprint in relation to the analysis period

	CO_2	EF
	t/track m	gha/ track m (CO_2* 0,338)
B3 rails	1,251599	0.42304
59Ri2 rails	2,315116	0.782509

Source: Authors' research

The results show that the 59Ri2 version has almost twice the ecological footprint of the B3 version.

5 Discussion and Conclusion

It appears that there are significant savings with respect to the reinforced concrete slabs and the embedding material, which make the B3 rail variant more favorable in terms of ecological footprint (too). It is evident that there are significant savings regarding reinforced concrete slabs and embedding material, which make the B3 rail variant more favorable in terms of ecological footprint. Even without a precise calculation, it is clear that the cost of the structure will also be lower than the other variant in the comparison, making it more eco-efficient. We therefore recommend the use of an ecological footprint in transport planning decisions, which provides decision-makers with a simple way of interpreting information on the complex environmental impact of the solution to be implemented.

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