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# Ecological Footprint Analysis of Tramway Track Structures

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The European urban landscape has been constantly evolving in the last 70 years since the Second World War. Thus, European cities are developing their own public transport networks. Urban rail transportation, namely trams, can be considered a mobility option with (1) high capacity, (2) relatively low life-cycle cost, and (3) low Greenhouse Gas (GHG) emission. Developing green urban transport systems requires, however, using a more comprehensive and complex approach. To do this, infrastructure operators should consider the environmental aspects of construction projects in the decision-making process. This article analyses the construction and maintenance issues of a very common and widespread tramway superstructure from the environmental point of view, using the methodology of ecological footprint calculations. Considering environmental impacts is highly recommended as early as the design stage by selecting the most suitable construction materials and technologies. Therefore, structural and vibration-damping solutions are compared that are equivalent in terms of technical suitability to highlight CO<sub>2</sub> emissions and ecological footprint during the production and life cycle of each building material. The results suggest that a multi-directional assessment can help to develop a more sustainable, liveable and environmentally friendly urban transport without major trade-offs. The article also shows how the ecological footprint of the designed track structure changes when it is optimised to minimise the environmental impact. Such a change could result in a reduction of up to 20 % in the ecological footprint.

# 1. Introduction

One of the biggest sustainability challenges of our time is the complex and sustainable development of cities, one of the key elements of which is the transformation of urban mobility infrastructure (Rydin et al., 2012). Preserving and improving the state of environmental health is a fundamental goal (Czédli and Varga, 2017). Designating and assessing the urban areas to be developed is a complex professional task (Varga et al., 2021). Optimising the urban passenger transport structure is an effective tool for low-carbon urban development, which requires significant innovation (Li et al., 2023). The biggest challenge of our time is to solve these new challenges (Csiszárik-Kocsir and Varga, 2023a), which are both individual and organisational (Csiszárik-Kocsir and Varga, 2023b). Traditional solutions are not able to solve these problems, but it is necessary to approach them with innovative tools (Csiszárik-Kocsir and Dobos, 2023). A globalised world requires us to maintain, expand and modernise both passenger and freight transport in our cities, within and between our countries, while meeting the ever-changing requirements (Varga et al., 2015). Better understanding, promoting and managing sustainable urban mobility is a very important tool for tackling the climate crisis (Chatziioannou et al., 2023).

The ecological footprint is an increasingly common and well-understood indicator of the environmental burden of metropolitan and agglomeration areas. A study by Harangozó et al. (2019) highlights that transport and mobility are key determinants of the ecological footprint (EF) of urban areas.

The importance of developing the tram network is far greater than its role in car-free transport. The development of tram networks can also promote the use of electricity generated from renewable sources, thus contributing to the advance of renewable energy (Hamburger and Harangozó, 2018). In this article, two possible variants of a

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so-called embedded track structure are compared, which is frequently found in the tram network of large cities, in terms of technical parameters and ecological footprint. In the article, an analysis of the ecological footprint of embedded rail structures is presented by examining two versions that adapt differently to environmental aspects. This adaptation results in a different ecological footprint.

## 2. Theoretical background

Due to the increasing demands placed on rail transport, such as noise and vibration loads and the reduction of life cycle costs, the use of embedded track superstructures is also gaining ground in Hungary, where they are mainly used on bridges, level crossings, tunnels and urban railway lines. Advantageous features of the design include (1) favourable noise and vibration damping properties, (2) homogeneous, flexible support along the length of the rail both horizontally and vertically, (3) minimal maintenance requirements, thus favourable life-cycle costs, and (4) in the case of DC traction typical of trams, stray currents protect the embedded rail against corrosion. It is important to note, however, that the track structure requires very precise workmanship and a high degree of technological discipline during construction and that the embedding material is expensive.

A common feature of the structures is that in the pre-formed rail channel, the rail "floats" in the casting material. To minimise the amount of casting material, the structure may contain cavities (PVC pipe) or pre-cast concrete shapes, or the amount of material to be installed may be reduced by the correct choice of the rail section used. There are two ways of adjusting the desired rail support factor: either by varying the thickness of the underpour or by placing elastic strips under the rail foot.

The appearance of the paved track structure with embedded rails is illustrated in Figure 1, with the newly built Etele Plaza in the background and a park on the roadside. The reason for showing this picture is twofold. At present, all the shopping centres in Budapest and, due to the specificities of urban development, the large-capacity factories "stuck" in the city centre are served by road. This logistical capacity could be replaced, at least in part, by freight transs. They can be a competitive alternative to road transport and a means to achieve sustainable urban freight transport. There are already working examples of this in Poland (Pietrzak and Pietrzak, 2021) and the Czech Republic (Zilka et al., 2021). Perhaps one of the best-known examples of this solution is the Dresden freight tram between the logistics centre of Volkswagen and the Volkswagen factory, which avoids over 200 truck movements per day through the city centre (Quak, 2011). In Hungary, the service was also available on BKV lines in Budapest, but by the turn of the millennium, it had virtually disappeared, giving way to the much more polluting service by road.



Figure 1: Paved tram track structure with embedded rails

There is one more observation to make in the picture. In big cities, there are more and more restrictions on cars entering city centres. This would make the existing road network unused, but it would not reduce transport needs, and it would also be necessary to create the possibility of access for special vehicles in these inner-city areas. To overcome this, there is an opportunity to redesign the inner-city road network to create a more liveable environment by reallocating track space. Transport needs and necessary accessibility can be addressed on the

paved tramway track, while the remaining areas can be dedicated to pedestrian and bicycle traffic, and even turned into green space, which is the basis for creating a healthy living environment.

The discourse on optimising the construction costs of embedded track structures in Hungary emerged in 2014. Even though correctly chosen parameters can lead to significant cost savings and more accurate compliance with environmental impact requirements, the practical design of embedded track structures is currently based on the examination of single variants and costly laboratory tests, and their optimisation is not addressed at all in Hungarian practice, and only rarely in international practice (Major and Kulcsár, 2014). The environmental impact associated with track structures is highly complex; in addition to the ecological footprint components associated with production and use, noise pollution can be a significant factor, which is strongly influenced by the type and condition of the track structures (Harangozó and Szerényi, 2012). Markine et al. (2000) present in their paper the optimisation of embedded track structures for several parameters. The properties to be optimised are summarised below.

- **Properties of elasticity:** the choice of the right type of embedding material, precisely designed pouring dimensions, and the use of elastic tapes where necessary can have a positive influence on the stresses in the rail, on the vertical and lateral deformation of the rail under vehicle load, and on the safety against vertical thermal expansion and gap opening due to weld breakage/rail fracture. Thus, these conditions must be considered in combination during optimisation.
- Rail system and rail quality: thanks to homogeneous, continuous bearing and lateral support, the stresses and deformations of the rail are more favourable than in ballast tracks, allowing the use of rail types with lower mass than in conventional designs.
- The quantity of the embedding material: the quantity of the embedding material is not independent of the spring constant to be designed, so optimisation is only possible by considering these two factors in combination. The quantity is influenced by the chosen rail type, the geometry of the rail channel and the embedding, the use of cavities (possibly pre-cast concrete shapes). Based on the known geometry, it is possible to determine the specific material consumption, which is the amount of embedding material per linear metre of rail.
- **Maintenance need:** an attempt can be made to define a maintenance requirement parameter based on the maintenance need of the structure designed, taking into account the intervention costs during the technical lifetime of the track.
- Acoustic and vibration properties: by choosing the right type of embedding material, reducing the "free" surface of the track, and interrupting the vibration bridge, better noise and vibration properties can be achieved than in the case of conventional tracks.

## 3. Methodology

In this article, the variations of the ecological footprint for two structural designs are examined. 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. While the reference structure does not require any relevant intervention, the other structure reduces vibration transmission by the installation of a flexible layer (see Figure 2), which in an urban environment contributes to improving the quality of life of the inhabitants and to preserving the integrity of the buildings themselves. It is important to stress, however, that the installation of a flexible layer can also represent unnecessary extra expenditure if the distance between the buildings to be protected is greater or their technical condition is more favourable. As our previous study has shown, the presented designs can be considered an eco-efficient solution compared to conventional embedded track structures (Major et al., 2023).



Figure 2: The performance of the investigated structures with and without under slab track mat (USTM)

In order to perform the comparative analysis, the four components shown in the following subsections were examined in detail. The specific CO<sub>2</sub> emissions for each material were all considered according to the Inventory of Carbon and Energy Database (ICE) v3.0 for 1 track meter (Embodied Carbon Footprint Database, 2022).

- rail steel,
- elastic embedding material,
- track slabs,
- USTM (under slab track mat).

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. Based on ICE database v3.0, the specific value of CO2 emissions is 1.27 kg CO<sub>2</sub>/kg (structural steel). In determining the amount of elastic embedding material, it was assumed that the thickness of the bottom layer of the embedding compound used was a uniform 20 mm. The specific volume is 16.22 L/track meter for rail B3. 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 value of CO2 emissions based on ICE V3.0 is 4.84 kg CO2/kg (flexible polyurethane foam). The specific volume of the concrete slab was first determined from its geometrical dimensions to calculate its own emission. Assuming a panel width of 2,200 mm, the specific volume of the slab was calculated to be 0.396 m<sup>3</sup>/track meter for a 180 mm thick slab. For concrete, a density of 2,500 kg/m<sup>3</sup> was assumed. Thus, the specific mass of the concrete for the B3 rail is 0.96 t/ track meter. Based on ICE V3.0, the specific value of CO2 emissions is 0.132 kg CO2/kg (precast concrete pavement). The mass of the reinforcing steel installed, with the previous simplifications, is 93.2 kg/track meter. Based on ICE V3.0, the specific value of CO<sub>2</sub> emissions is 1.99 kg CO<sub>2</sub>/kg (reinforcing steel). In determining the amount of USTM, it was assumed that the thickness of the layer was a uniform 25 mm. The specific volume is 55.0 l/track meter for rail B3. 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 value of CO2 emissions based on ICE V3.0 is 4.84 kg CO2/kg (flexible polyurethane foam).

To determine the  $CO_2$  value from the transport of each component, the specific masses per 1 track meter were calculated. The source of the initial data is Treibhausgasemissionen durch die Schieneninfrastruktur und Schienenfahrzeuge in Deutschland (Mottschall and Schmied, 2013). The transport distance for the rail is 500 km on railway. The specific emission is 26.7 g/tkm. The transport distance for the embedding material is 500 km on road. The specific emission is 199.3 g/tkm for solo truck (>26 t). The transport distance for the track slab is 250 km on the road. The specific emission is 199.3 g/tkm for solo truck (>26 t). The transport distance for the uSTM is 500 km on the road. The specific emission is 199.3 g/tkm for solo truck (>26 t). Results and discussion

Our ecological analysis of the two designs under consideration is summarised in Table 1.

Component	Material kgCO <sub>2</sub> /track m	Transport kgCO <sub>2</sub> /track m	ΣCO <sub>2</sub> kgCO <sub>2</sub> /track m	Useful life y	Specific value kgCO <sub>2</sub> /track m/y
Rail	138.7	1.458	140.158	15	9.344
Embedding	70.7	1.455	72.155	15	4.810
Track slab	316.3	47.847	364.147	60	6.069
USTM	240.0 / 0.0	4.930 / 0.0	244.930 / 0.0	60	4.080 / 0.0
				Σ	24.303 / 20.223

Table 1: Analysis from an ecological perspective – with and without USTM

Based on the results of Table 1, it is evident that when optimising the same track structure types, it is possible to reduce CO<sub>2</sub> emissions by selecting the appropriate superstructure variant. For our investigation, the analysis period was expediently set equal to the maximum useful life of 60 y. The ecological footprint, expressed in global hectares (gha), can be defined as the product of CO<sub>2</sub> emissions in tons multiplied by the Footprint Intensity of Carbon published by the Global Footprint Network (Lin et al., 2018). Based on our calculations, the ecological footprint values for each design are summarised in Table 2.

Table 2: The r	result of the	ecological	analysis –	1.
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Superstructure	CO <sub>2</sub>	EF
	t/track m	gha/ track m (CO2* 0,338)
B3 rails without USTM	1.2134	0.4101
B3 rails with USTM	1.4582	0.4929

The values in Table 2 can be compared to the biocapacity, which is the capacity of a given area to support life. The biocapacity (BC) per track metre can be calculated by multiplying the area by the conversion factors given by the GFN. Of these, the equivalence factor (EQF) allows conversion between land use categories, in this case a multiplier of 2.5, and the yield factor (YF) is a country-specific adjustment, which for Hungary is a multiplier of 1.15262 according to the latest data (Lin et al., 2018) The ecological footprint to biocapacity ratio shows how many times bigger the ecological footprint of a given area is compared to its biocapacity (Table 3). The lower this value, the better, and the optimal situation would be if it did not exceed 1.

Table 3. The result of the ecological analysis – 2	Table 3	The	result	of	the	ecological	analys	sis –	2.
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Superstructure	EF gha/ track m (CO <sub>2</sub> * 0,338)	BC gha/track m (2.2×2.5×1.15262)/10000	EF/BC
B3 rails without USTM	0.4101	0.000634	646
B3 rails with USTM	0.4929	0.000634	777

From the calculations carried out, it is apparent that, in order to adapt to the environmental demands, a 20 % difference in CO<sub>2</sub> emissions and, thus, in the ecological footprint can be observed between the two structures by incorporating elastomer mats into the track structure.

The results are relevant and significant for the sustainability research field. Research on transport sustainability typically focuses on use, and the results bring new perspectives to the transport sustainability debate. The research results presented in this article support the need to consider lower-carbon solutions for the construction of transport infrastructure.

## 4. Conclusions

This article demonstrates how the use of paved track structures with embedded rails can revitalise inner-city districts and serve increased transport needs in a much more environmentally friendly way than the current road freight transport. This would also require traffic engineers to ensure that tramway traffic has an advantage over road traffic and can, therefore, have a significantly higher capacity. The article also illustrates how the ecological footprint of the designed track structure changes when it is optimised to minimise the environmental impact. The results show that even though using USTM increases the environmental impact of B3 rails by approx. 20 %, this type of track structure still has more favourable characteristics than the more commonly used 59Ri2 regarding its (1) financial costs, (2) environmental impacts, and (3) noise and vibration emissions. Therefore, the policy recommended is that decision-makers should take into consideration a more comprehensive set of indicators at the selection of the projects' technical parameters. Namely, although using B3 rails with USTM may have both higher financial cost and environmental impact, it is recommended to use it in densely populated urban areas. The limitation is, however, that the level of noise and vibration is not considered exactly in this paper, so further analyses are needed to determine the distance needed between the tracks and the neighbouring buildings where the additional construction cost of USTM and the negative externalities of noise and vibration are equal.

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