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Sustainable management of railway infrastructure – a case study in analyzing the fate of copper along railway tracks

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1 EXECUTIVE SUMMARY

Railway systems can be looked at as metabolic systems: on one hand, they require an input of material supply to construct, operate and maintain the network. On the other hand, their activities result in wastes and emissions like off-gas, solid and liquid residues, and dissipative losses from wear, corrosion, and weathering. These off-products are often regulated by the EU and member states, e.g. by the EU Water Framework: member states have to detect diffuse emissions as prerequisite first step to keep substance concentrations in environmental media on an acceptable level. Thus, railway infrastructures and rolling stock components must be controlled in view of dissipative losses to the environment.

Track ballast involves the largest amount of mass flow in the life cycle of every railroad infrastructure. To maintain its function, it has to be renewed and refined after 2-3 decades. While most track ballast can be recycled, some residues of recycling must be disposed of in landfills. Recent studies show, that track ballast contains various heavy metals such as copper which may prevent recycling and which require disposal in expensive controlled sanitary landfills.

The goal of this paper is 1. to identify the sources and pathways of copper entering track ballast and environmental media, 2. to assess implications of copper content for recycling and landfilling, 3. to propose new, cost effective and ecologically sound prevention and reduction strategies, and 4. to use the findings for proposing a network-wide intelligent environmental monitoring system to avoid future overloads in ballast and environment.

In order to reach these objectives, copper flow studies were performed in theory and practice. Information on abrasion of contact wire, losses of copper by brake systems, and geogenic copper content was combined in a model to roughly assess flows and stocks of copper in track ballast and soil. Based on these results, copper concentrations were measured in the field in order to test the model.

The results of this study show, that the three sources gravel, contact wire and brake pads are of equal importance for the copper concentration of the railroad stretch investigated. For future management of track ballast, the following three measures are recommended: First, purchase gravel of low geogenic copper content to prevent that copper concentrations in track ballast exceed existing standards for recycling and landfilling. Second, develop new brake systems that contain much less copper. Third, start fundamental research about alternative catenary material as well as transmitting energy from the contact wire to the locomotive without material losses.

In summary, the study shows 1) that much of today's wastes from railroad systems can be prevented by a goal-oriented choice of products, and 2) that a monitoring system aimed at recognizing critical substance loads ensures legal compliance and environmental compatibility.

2 INTRODUCTION

Track ballast causes the largest mass flow while managing the superstructure of a railway. The annual fresh ballast demand of the Austrian Federal Railways (ÖBB) is around 0,6 Mio. tonnes, the demand of the German Federal Railway AG (DB) amounts to about 4 Mio. tonnes per year (Becker et al., 2004). Pollutants from the operational phase of the railway have a significant impact on the quality and usable quantity of the old ballast.

In some sections of the ÖBB network the copper content of the old ballast exceeds the limits for replacement or recovery. This waste must be disposed of costly. The objective of the research work on behalf of ÖBB was to identify and quantify sources and pathways of copper entering the railway ballast. The results form the basis in order to lower copper concentrations in the removed ballast and thereby avoid costly landfilling. With the insights gained, the long-term ballast management can be optimized in terms of resource conservation and environmental protection, the two main goals of waste management. In addition, basics for developing a strategy reducing copper emissions are proposed.

3 COPPER BALANCE OF ONE KILOMETRE RAILWAY LINE

The knowledge about sources, pathways and sinks of copper is a prerequisite first step in order to evaluate a) the prorated contribution of each copper source, and b) the relevance of copper accumulation in environmental media and ballast fractions. In this chapter, the procedure for analyzing the fate of copper within one kilometer railway line is presented as well as the results – the copper balance.

3.1 Method: substance flow analysis (SFA)

SFA is used to account for the source, pathway and sinks of materials within a defined system boundary. Since the system is subject to the mass conservation law, SFA can be easily verified and checked for completeness. SFA is based on a standard ÖNORM method (Österreichisches Normungsinstitut, 2005; Österreichisches Normungsinstitut, 2005) and is therefore often used as a basis for environmental impact assessment, life cycle analysis and waste management concepts, but also increasingly used for issues of resource management. The application of the method on the rail infrastructure is instrumental to establish a knowledge base for effective resource and environmental management of infrastructure assets. The open access software STAN is used to support substance balancing (Rechberger et al., 2010).

3.2 SFA system description

To investigate into the substance flow system, system boundaries, relevant processes, flows and stocks are determined. After the selection of a specific track section along the Austrian main east/west route, the so called Westbahn (see Figure 1),

(1) the spatial system boundary is chosen (see Figure 2).
(2) the temporal system boundary is set for one year. The results are extrapolated according to the ballasts lifetime of two decades.
(3) copper is selected as relevant substance.
(4) the relevant processes are chosen, whereat the processes “contact wire”, “rolling stock” and “track ballast” are within the system limits. Outside the system boundary are the processes “planum / surface”, “adjacent land”, “atmosphere”, and “landfill”.

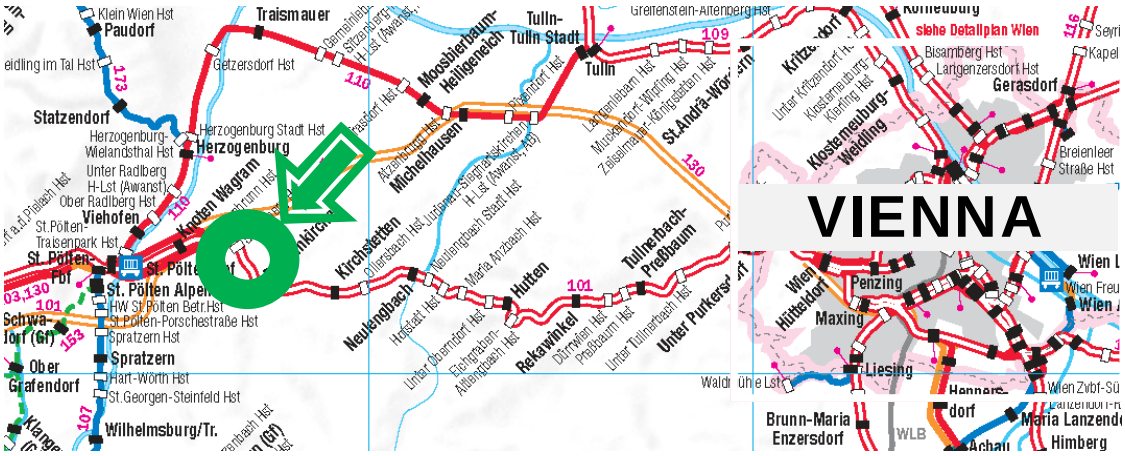

Figure 1: Location of the track section investigated.

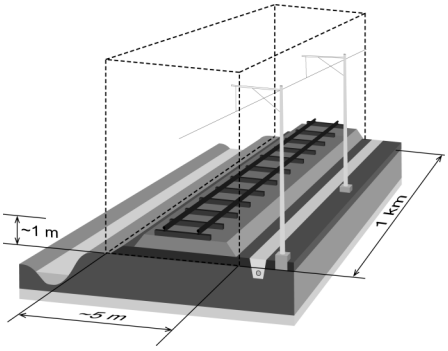

Figure 2: Spatial system boundary.

Figure 3: Sampling ballast in the field.

Figure 4: Screening and pulverizing ballast samples.

3.3 SFA model quantification

The procedures for quantifying the material flow model (Figure 5) consist of:

(1) Distinction of the geogenic and anthropogenic copper content in different grain fractions of track ballast samples by laboratory methods, and measurements of copper concentrations in the soil along railway tracks (Figure 3, Figure 4).

(2) Determination of the emission flows resulting from the rolling stock and infrastructure components, based on literature data and technical information from ÖBB. The values are given for one kilometer railroad.

The plausibility of the model is checked by comparing the total copper content in the samples with results calculated on the basis of literature values.

3.4 SFA results: Copper balance of one kilometer railway line

The railroad segment investigated runs mainly horizontal in open land with a length of one kilometer. Trains under normal conditions neither accelerate nor reduce their speed during this section. Thus, the situation represents a segment with low abrasion and emission loads.

Figure 5 displays the corresponding copper balance. The total operational copper emissions are shared in ratio of 80/20 on the “catenary wire” and “rolling stock” components (Figure 5). About 80% of the operational copper losses cross the system boundary, which is copper transported into the atmosphere, and accumulated in the planum and the adjacent soil as well as on the surface of the rolling stock (Figure 6). The remaining 20% of copper losses enter the track ballast with a mass flow of about 3,7 kg Cu/a. The current copper emissions entering “track ballast” result from the sources “catenary wire” and “rolling stock” in similar size. Cast iron brakes are mainly responsible for copper emissions. It is likely that this source is much more important on routes with increased brake use, such as railway stations and maneuvering areas.

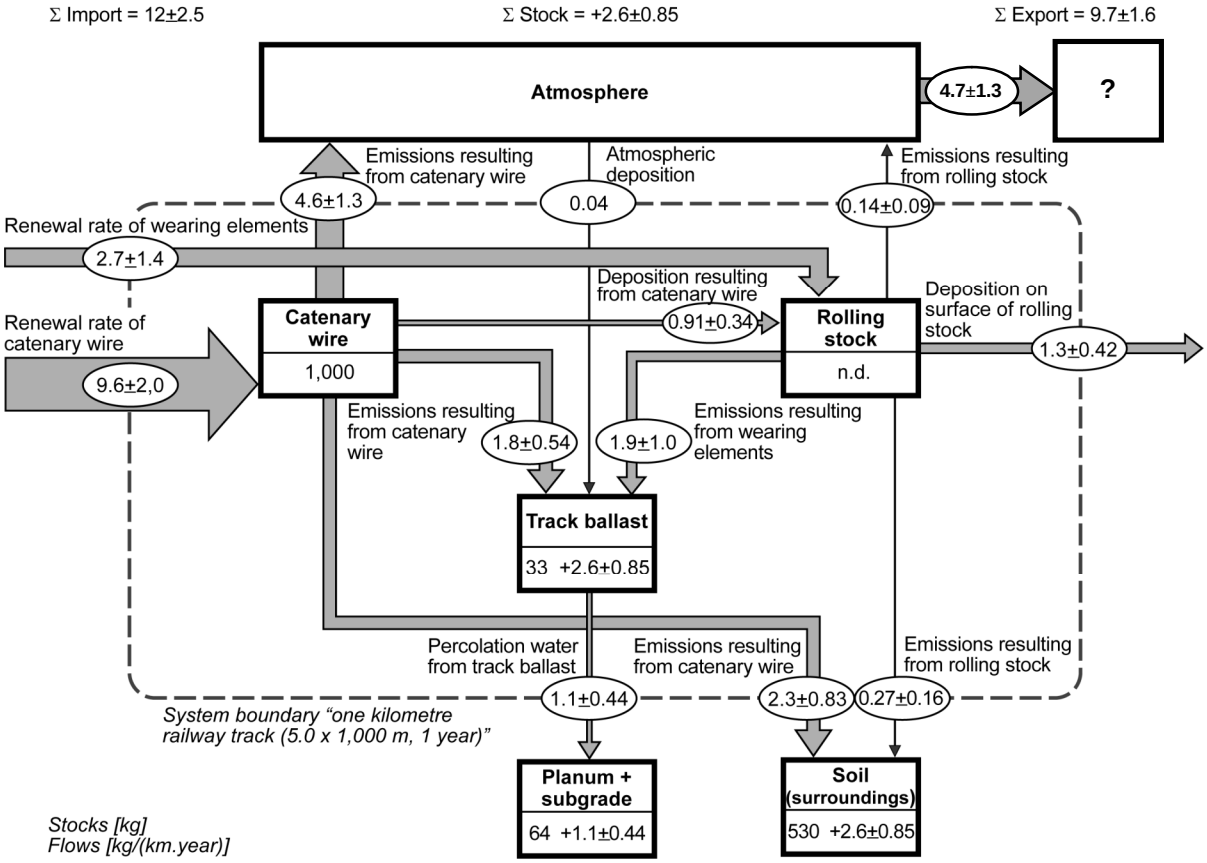

Figure 5: Copper balance for one kilometer railway line (Müller et al., 2008, S. 34)

Figure 6 displays the alteration of copper stocks based on the copper balance (Figure 5). The copper stocks "catenary wire" and "rolling stock" decrease while the copper stocks "track ballast" and "environment" increase. In other words, "track ballast" and "environment" are copper sinks.

Track ballast as copper source and sink

The results show the importance of the ballast a) as source of Cu: fresh ballast contains about 33 kg copper (~10 mg Cu/kg ballast) of geogenic origin. b) as sink for Cu: about 20% of the annual emission load accumulates in the ballast. Hence, the copper stock in the ballast doubles within 13 years because of operational copper emissions.

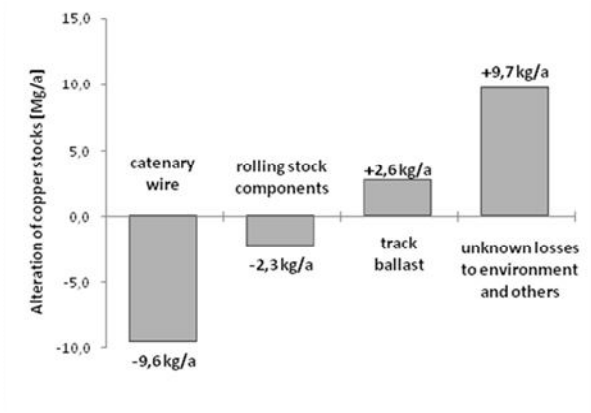

Figure 6: Alteration of copper stocks within one kilometer railway line.

Distribution of copper accumulation within the ballast body

The accumulation of copper affects mainly the fine fraction, which is sorted out and disposed of by treatment technologies. Laboratory results indicate for a specific track section that a) the copper concentrations in the fine fraction (d < 2 mm), are about 6 times higher than those in the coarse fraction (d > 6,3 mm), and that b) the anthropogenic portion in the fine fraction (d < 2 mm) is about 80%, the geogenic portion is about 20% (Müller et al., 2008, p. 49 ff.). After 20 years in operation the copper stock in the track ballast is about 85 kg. About 60% of this copper results from the operational phase. The remaining 40% of the copper is of geogenic origin.

4 HANDLING OLD BALLAST FROM A WASTE MANAGEMENT PERSPECTIVE

Track ballast represents the biggest material stock and flow over the railway infrastructure lifetime. Waste management goals require that the use of ballast is optimized in view of conserving primary resources and minimizing environmental pollution. Material balances deliver basic information that is needed to estimate future legal compliance and to evaluate the effectiveness of recycling and treatment technologies.

4.1 Material balances as knowledge base

The copper balance (Figure 5) is used to roughly estimate the ballast flows over 20 years lifetime. Figure 7 and Figure 8 display material flows and stocks of one kilometer railway line from a waste management perspective. It is crucial to focus on the both the level of goods and the level of copper. The level of goods is relevant to evaluate the conservation of primary resources and the level of copper is relevant to evaluate the compliance with legal standards regarding specific substances. The following assumptions are made:

- About 3.300 metric tonnes of ballast are dismantled, refined and cracked. The “on-site treatment technology” seperates 55% of the dismantled ballast for further reuse, 15% fine material and 30% coarse material are sorted out.
- The flows “reused ballast” and “coarse material” have the same copper concentration as the fresh ballast (10 mg Cu/kg ballast).

Results from material balancing (Figure 7) show that: a) 1.500 tonnes of old ballast, containing 500 tonnes of fine material and 1000 tonnes of technically useless ballast has to be disposed of, and b) 1.500 tonnes of fresh ballast has to be installed for keeping the ballast stock constant.

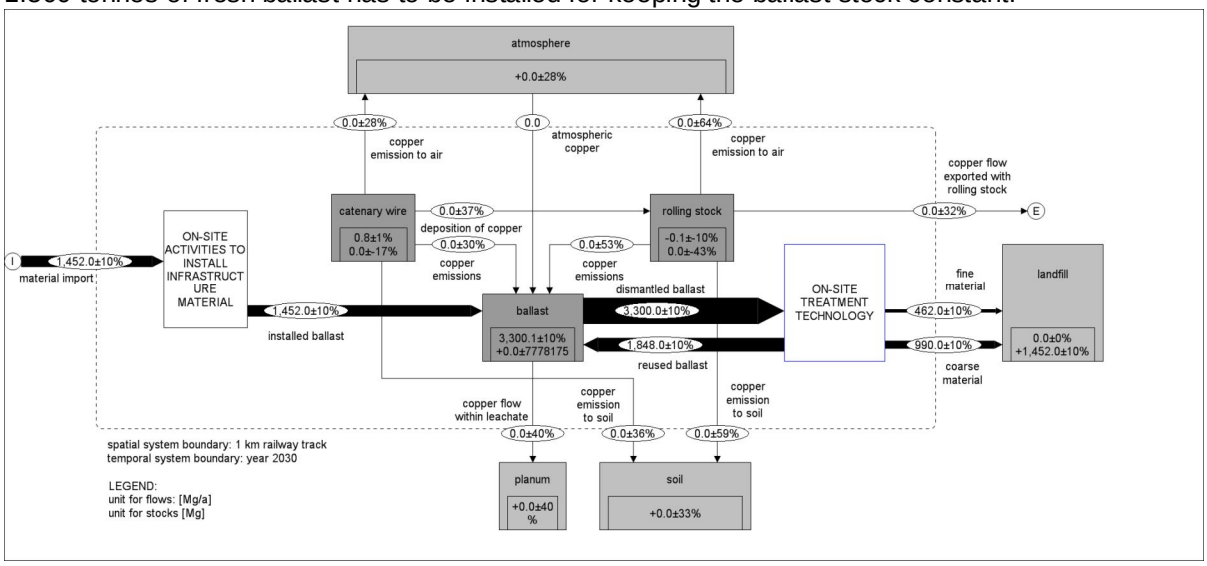

Figure 7: Material balance of one kilometer track in the year of renewing the track bed.

Results from copper balancing (Figure 8) show that: a) 85 kg copper are dismantled by removing old ballast, b) 15 kg copper are imported to the track by installing fresh ballast, 18 kg enter the track by reusing recycled ballast, and c) 67 kg copper are disposed of in landfills.

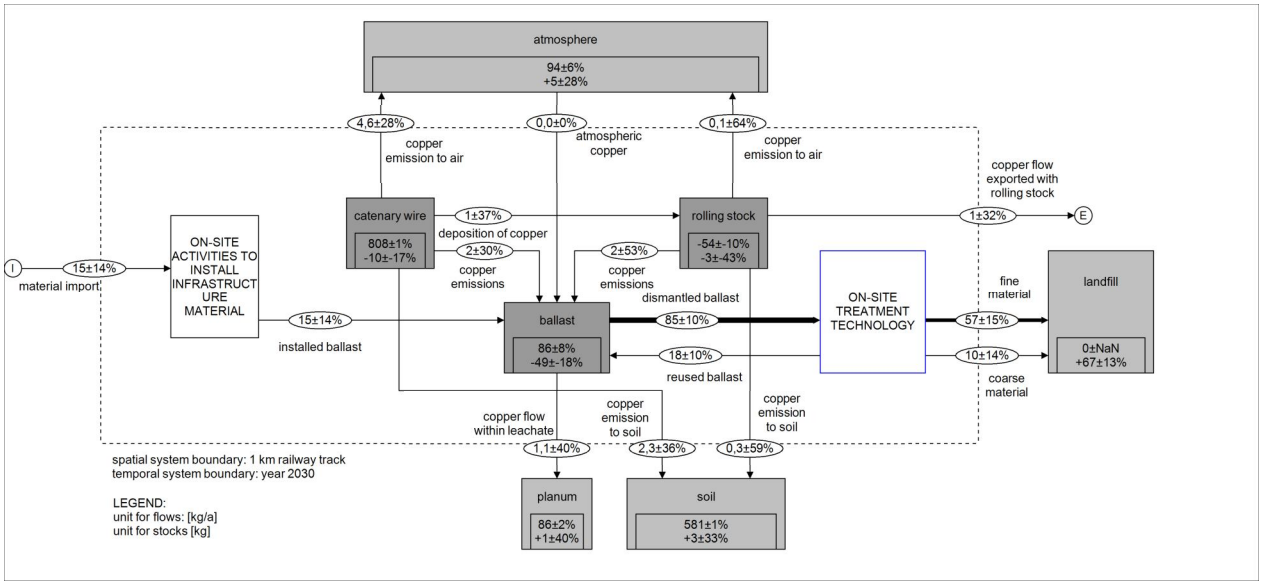

Figure 8: Copper balance of one kilometer track in the year of renewing the track bed.

4.2 Compliance with recycling standards and landfill directive

The estimated copper content of specific ballast flows is used to test their compliance with a) recycling limits according to a national agreement determining the quality recycling products, and b) disposal limits according to the Austrian Landfill Directive.

Quality criteria of recycling products are displayed in the Austrian Federal Waste Plan 2006 (BMLFUW, 2006). The criteria are based on a national agreement between official authorities and stakeholders in the waste management sector. According to this agreement, the fine material exceeds the two limits for recycling 4 and 14 years respectively after installation the ballast (Figure 9). Consequently, the fine material is incapable of recycling and has to be disposed of.

The criteria for disposing of construction waste is determined in the Austrian Landfill Directive (Republik Österreich, 2008). According to the law, old ballast can be disposed of up to a total copper content of 500 mg Cu/kg. The estimated total copper content of the excavated fine material is about 110 mg Cu/kg. Consequently this construction waste flow can be disposed of.

The estimation of copper content in ballast fractions based on SFA results ensures early recognition of future overloads. This supports the development of effective measures to comply with recycling and disposal limits.

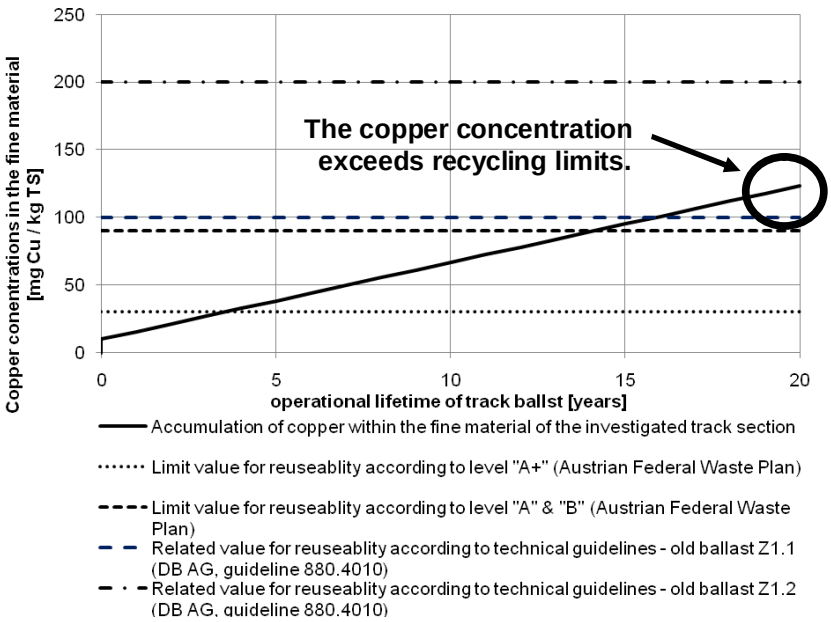

Figure 9: Copper accumulation over time within the fine material of track ballast.

5 CONCLUSION

The two main goals of waste management are environmental protection and resource conservation. Therefore, it is crucial that producers of waste identify those key material flows and stocks which are likely to infringe these goals and thus have to be routinely monitored and controlled. In this study about sustainable management of railway infrastructure, the tool substance flow analysis (SFA) is successfully applied to determine material balances. This knowledge is essential for three reasons: First, SFA results point out key sources of contaminants in track ballast. Therewith, effective measures can be developed to optimize recycling rates and minimize environmental pollution. Second, SFA results allow predicting future construction waste flows in terms of quality and quantity. Third, SFA results provide a common understanding of copper flows for all stakeholders involved (generator of pollution, waste managers, regulator, others).

Source oriented measures reducing copper loads

SFA is instrumental for a source oriented waste prevention strategy by delivering the prorated contribution of each copper source. For such a strategy, the focus must by laid on a) reducing the abrasion of the catenary wire and the brake pads, b) new brake systems that contain much less copper, and c) on the choice of ballast with low geogenic copper concentrations.

Ballast, water and soil management

The study reveals, that 80% of the copper emissions occurring during the operation of 1 km railway line are lost to the environment and do not enter the ballast body. Up to now, the fate and effects of the 80% of copper emissions have not yet been investigated systematically, and therefore reliable information about potential environmental impacts of most of the copper is lacking. Nevertheless, the remaining 20% taken up by ballast are important for waste management, as old ballast has to be handled as waste and hence must be managed carefully to fulfill the goals of waste management as well as to minimize costs.

Liberalization of the railway sector as environmental challenge

Based on these results, liberalization of the railway sector poses a new challenge for infrastructure managers who are responsible that environmental management complies with regulations. As presented in this study, the main source of Cu is not the original Cu content in the ballast, but the erosion of the catenary wire and the brake systems, which are caused by the operation of the railways. How are the copper loadings within a liberalized railway system to be allocated to the different users of the network? SFA constitutes an objective information base for all stakeholders (waste generators, railway operators, responsible authorities etc.) by identifying and linking emission sources, pathways and sinks. The results may serve as a complementary basis for the design of route prices, procurement processes or technical guidelines for operating trains in order to minimize contaminated ballast, soil and water.

6 OUTLOOK: INTELLIGENT ENVIRONMENTAL MONITORING ALONG RAILWAY TRACKS

The local copper study revealed that 20% of copper emissions enter ballast fractions. The remaining 80% enter mainly environmental media. Despite some excellent reports in this field, there is no systematic approach that identifies available substance sinks and related limitations. Consequently, an efficient and effective monitoring system can be designed: it is not necessary to monitor the whole railway network; it suffices to analyze and record hot spots of emission sources. Focusing on stations, shunting areas and downhill sections allows early recognition of future overloads within ballast and environment.

Subsequently, the core ideas about a monitoring strategy for railways were integrated into the EU Framework Programme 7 Coordinated Action InfraGuidER. This action was initiated in cooperation with UIC to pool existing knowledge of Infrastructure Managers in order to improve environmental performance of railways.

6.1 Goal

The goal is to develop an intelligent environmental monitoring system that allows 1) early recognition of harmful accumulation of substances in environmental media along railway tracks, 2) setting priorities that focus on relevant substance flows, and 3) taking cost effective design and management options for building and operating railway lines.

6.2 Approach

In order to reach the objective, a two line approach including 1) the development of an environmental monitoring scheme for railway infrastructure, and 2) a case study are proposed.

First, the monitoring concept is set up in theory based on a rigid scientific framework.

a) Development of a goal oriented evaluation scheme that a) characterizes environmental risks, and b) compares anthropogenic and geogenic substance flows/stocks in ballast fractions and environment along railway tracks.
b) Development of an analyzing scheme by identification of spatial and temporal distributed emission/imission patterns. Therefore localized substance concentrations, based on SFA approach, have to be recognized. Together with the substance properties (degradation, sorption, ecotoxicity) the mobility/losses of each substance can be quantified for different types, operating states under varying loading conditions (Burkhard et al., 2010).
c) The linkage of the analyzing and evaluation scheme assesses the localized quality of ballast, soil, water and air. Relevant sinks are recognized in time throughout the railway system and visualized by geographical information systems (Figure 10).

Second, the intelligent monitoring system developed is applied to one railway system in order to test its' applicability and benefit for all stakeholders (Infrastructure Mangers, Railway Operators, legal authorities). Finally, Recommendation of effective and efficient measures in order to avoid future overloads in environmental compartments and ballast fractions.

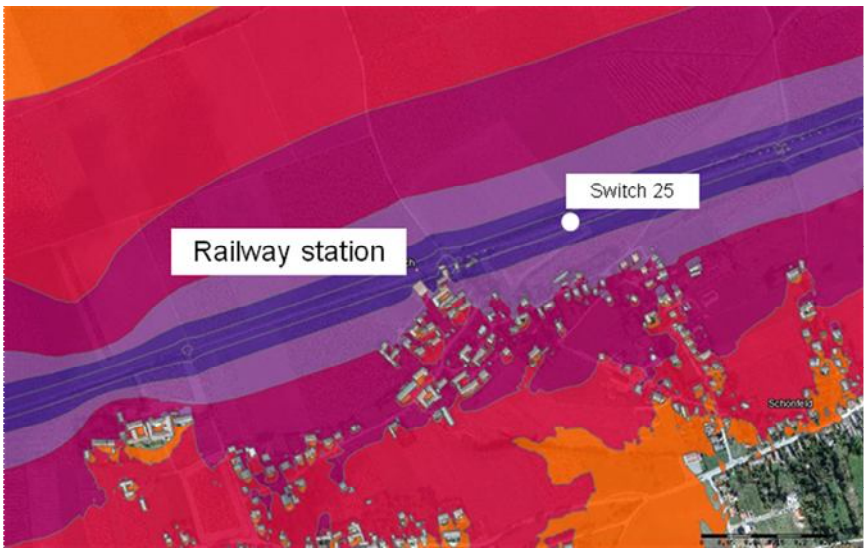

Figure 10: GIS based visualization of emission rates caused by diffuse emissions along railway tracks (hypothetical example, picture source: www.lebensministerium.at, modified).

6.3 Expected results

- An effective and efficient environmental monitoring scheme taking railway systems into account. The system gives advice to set measures right in time if potential environmental overloads are predicted.
- Technical guidelines how to design and operate railway sub-systems. The measures should be categorized according to their cost/effective value of each option. Generally, the design options focus on three weak points of the railways material system: 1) emission sources (e.g.: substitution of specific substances at the stage of procurement), 2) substance pathways (e.g.: drainage system), and 3) sinks of emissions released (e.g.: soil cleaning technologies).

7 ACKNOWLEDGEMENTS

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