Supplementary material for

Dissipation of Tungsten and Environmental Release of Nanoparticles from Tire Studs: A Swedish Case Study

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1. Input data for estimation of tungsten flows

The input data parameters for the tungsten flow calculations are described in Table S1 and the numerical values used for these parameters are presented in Table S2.

Table S1. Description of input data parameters for the tungsten flow calculations. WC-Co=tungsten carbide with cobalt.

Parameter	Description
CALCULATION OF TUNGSTEN FLOWS	
Parameters for estimating tungsten flows upstream the use phase	
$S_{ti, ore}$	Share of total input that comes from ore. Total input refers to the sum of the input of virgin tungsten material and tungsten scrap going into the system.
$S_{ti, scrap}$	Share of total input that comes from scrap. Total input refers to the sum of the input of virgin tungsten material and tungsten scrap going into the system.
$S_{scrap, cp}$	Share of scrap that is recycled through the chemical process for recycling of tungsten
$S_{scrap, zp}$	Share of scrap that is recycled through the zinc process for recycling of tungsten
$S_{mining\ loss}$	Share of tungsten lost in the mining process
$S_{hm\ loss}$	Share of tungsten lost in the hydrometallurgy process
$S_{pym\ loss}$	Share of tungsten lost in the pyrometallurgy process
$S_{pom\ loss}$	Share of tungsten lost in the powder metallurgy process
Parameters for estimating tungsten flows in the use phase and use phase release as WC-Co nanoparticles	
m_{pin}	Weight of a WC-Co pin
$S_{pin, W}$	Share of tungsten in a WC-Co pin
N_{ts}	Number of studs per tire
N_{tires}	Number of tires per passenger car
$N_{new\ cars, i}$	Number of passenger cars that were new on the Swedish market in year *i*
S_i	Share of passenger cars with studded tires in Sweden in year *i*
S_{wts}	Share of the total number of tire studs that remains in a tire after use and has thus not been lost in the form of whole tire studs during use
$S_{wts\ lost\ worn}$	Share of the total wear of a pin during the studded tire's lifetime that was worn away before the tire stud was lost whole from the tire
$S_{pin\ worn}$	Share of a pin that is worn during the studded tire's lifetime
$S_{re, NP}$	Share of the use phase WC-Co particle release that is nanoparticles

Parameter	Description
Parameters for estimating tungsten flows downstream the use phase	
$S_{scrap\ tires,\ c}$	Share of scrap tires that are collected and treated in various ways
S_{cement}	Share of treated scrap tires that are combusted in cement production
S_{plant}	Share of treated scrap tires that are combusted in heat and power plants
$S_{granulation}$	Share of treated scrap tires that are used in granulation
$S_{construction}$	Share of treated scrap tires that are used in construction works
$S_{reuse\ other}$	Share of treated scrap tires that are reused for other purposes

Table S2. Data for calculation of tungsten flows, representative for the year of 2015, in the base case and the low and high values applied in the sensitivity analysis. The abbreviation wt-% stands for weight-%. WC-Co=tungsten carbide with cobalt.

Parameter [unit]	Base case	Low	High	Description	Reference
CALCULATION OF TUNGSTEN FLOWS					
Data for estimating tungsten flows upstream the use phase					
$S_{ti, ore}$ [wt-%]	76	-	-	We assume that global figures are applicable to this study.	Leal-Ayala et al. (2015)
$S_{ti, scrap}$ [wt-%]	24	-	-	We assume that global figures are applicable to this study.	
$S_{scrap, cp}$ [wt-%]	50	-	-	We assume that global figures are applicable to this study.	
$S_{scrap, zp}$ [wt-%]	50	-	-	We assume that global figures are applicable to this study.	
$S_{mining\ loss}$ [wt-%]	25	10	43	The base case value was chosen following the reference. Losses in the beneficiation process can vary between 10 to 43%, which was used as a low and high value, respectively. We assume that global figures are applicable to this study.	
$S_{hm\ loss}$ [wt-%]	4	-	-	Loss in the process of manufacturing ammonium paratungstate (APT) from concentrates. We assume that global figures are applicable to this study.	
$S_{pym\ loss}$ [wt-%]	1	-	-	Loss in the process of converting APT into tungsten metal powder. We assume that global figures are applicable to this study.	
$S_{pom\ loss}$ [wt-%]	1	-	-	Loss in the process of converting tungsten metal powder into WC-Co. We assume that global figures are applicable to this study.	

Parameter [unit]	Base case	Low	High	Description	Reference
Data for estimating tungsten flows in the use phase, and use phase release as WC-Co nanoparticles					
m_{pin} [g]	0.3	0.2	0.4	Range of the approximate weight of pins. (The weight of a whole tire stud is about 1.1 g.) The average value was applied in the base case.	Vogler (2016), Peltola and Wikström (2006), Gustafsson (2001)
$S_{pin,\ W}$ [wt-% W]	80.5	75	86	WC-Co pins contain 80-92 wt-% WC. The wt-% of tungsten in a WC-Co pin was estimated based on knowledge of the wt-% of tungsten in WC. The wt-% of tungsten in WC is approximately 94 wt-%, based on the molar mass of tungsten and carbon, which is approximately 184 g/mol and 12 g/mol, respectively. The average value was applied in the base case.	Vogler (2016)
N_{ts} [-]	127	119	135	An average number for the tire studs in a studded tire at 127 with a standard deviation of 8 is provided by the reference who conduct a survey on studded tires in some storage facilities for tires in Sweden.	Hjort et al. (2017)
N_{tires} [-]	4	-	-	Passenger cars typically have four tires.	
$N_{new\ cars,\ i}$ [-]	362 000	229 000	388 000	New registered passenger cars in Sweden 2015 was used in the base case. The low and high value are the lowest and highest number for newly registered cars in Sweden during the period from 2007 to 2016 being 229 000 in 2009 and 388 000 in 2016, respectively.	Transport Analysis (2016), Transport Analysis (2017)
S_i [-]	0.663	0.636	0.723	Estimate for Sweden in the first quarter, January to March, of 2015 was used in the base case. The low and high value are the lowest and highest number obtained from the reference for the share of cars with studded tires in Sweden during the period from 2005 to 2015 being 63.6% in 2014 and 72.3% in 2005, respectively.	Swedish Transport Administration (2015)

Parameter [unit]	Base case	Low	High	Description	Reference
S_{wts} [-]	0.796	0.605	0.987	An average share of tire studs left on tires of 79.6% with a standard deviation of 19.1% is provided by the reference who conduct a survey on used studded tires in some storage facilities for tires in Sweden. This give an indication of the number of tire studs left in the tires after use and it is assumed to represent the number of studs left in the tires when they are entering the waste management phase.	Hjort et al. (2017)
$S_{wts\ lost\ worn}$ [-]	0.5	0	1	As a low estimate, it is assumed that the whole tire studs lost have not been worn at all. As a high estimate, it is assumed that the whole tire studs lost have been worn as much as the tire studs that remain in the tires until those are scrapped. The average value was applied in the base case.	Assumption by the authors
$S_{pin\ worn}$ [-]	0.75	0.5	1	Approximately 75% of the weight of the pin is lost due to wear based on the reference. 50% and 100% was applied as a low and high estimate, respectively.	Vogler (2016)
$S_{re,\ NP}$ [-]	0.075	0.05	0.1	Below 10 wt-% of tungsten-containing particles in road runoff from a Swedish highway were identified by the reference as less than 450 nm. In turn, the majority of these particles were in the size range of 15-120 nm according to the reference. Based on this, 10% was applied as a high value, 5% as a low value and 7.5% was used in the base case. A more detailed description is provided in Section 3.2 in the article.	Tuoriniemi (2013)
Data for estimating tungsten flows downstream the use phase					
$S_{scrap\ tires,\ c}$ [-]	0.975	0.95	1	This share of all Swedish scrap tires from different types of vehicles, including passenger cars, are collected and treated. At least a 0.95 share is collected. The average of 0.975 was used in the base case while the range 0.95 to 1 was used as a low and high value, respectively.	Svahn (2016)
S_{cement} [wt-%]	17	-	-	SDAB is responsible for the end-of-life treatment of tires in Sweden according to the producer liability. The data is valid for the year of 2015. We assume that studded tires are equally distributed between these different treatment types.	SDAB (2017)
S_{plant} [wt-%]	27	-	-		
$S_{granulation}$ [wt-%]	34	-	-		
$S_{construction}$ [wt-%]	12	-	-		
$S_{reuse\ other}$ [wt-%]	10	-	-		

2. Tungsten flow calculations

The tungsten flow parameters quantified in the calculations are described in Table S3 and shown in Figure S1. Transfer coefficients are provided in Table S5. All flows were estimated as flows of tungsten, while the use phase release were estimated both as flows of tungsten and WC-Co. The quantified flows of tungsten related to the use of studded tires in Sweden, from extraction to waste management, are based on an estimation of the flow of tire studs to the use phase (F_{13}) and an estimation of the flow of tungsten going out from the use phase to the waste management phase ($F_{16} + F_{17}$). These estimations are described in the article where the flows F_{13} and ($F_{16} + F_{17}$) are denoted $F_{to\ u,\ i}$ and $F_{to\ wm,\ i}$, respectively. The description of how F_{13} and ($F_{16} + F_{17}$) were estimated will be described in more detail in this section compared to the description in the article. Based on these two estimates, the use phase losses and all other flows upstream and downstream the use phase were quantified under the assumption of steady state.

Table S3. Description of calculated parameters in the tungsten flow calculations, see also Figure S1.

Parameter	Description
F_1	Total input of tungsten as ore and scrap to the system
F_2	Tungsten in ore to the mining process
F_3	Loss of tungsten in the mining process
F_4	Tungsten in concentrates from the mining process
F_5	Tungsten in scrap
F_6	Tungsten in scrap that is recycled through the chemical recycling process
F_7	Loss of tungsten in the hydrometallurgy process
F_8	Tungsten in ammonium paratungstate (APT) from the hydrometallurgy process
F_9	Tungsten in scrap that is recycled through the zinc recycling process
F_{10}	Loss of tungsten in the pyrometallurgy process
F_{11}	Tungsten in tungsten metal powder from the pyrometallurgy process
F_{12}	Loss of tungsten in the powder metallurgy process
F_{13}	Use of tungsten in tire studs in passenger car tires (denoted $F_{to\ u,\ i}$ in the article)
F_{14}	Tungsten in whole tire studs lost during use (denoted $F_{wts,\ lost,\ i}$ in the article. $F_{14} + F_{15}$ is denoted $F_{losses\ u,\ i}$ in the article)
F_{15}	Tungsten in particle release from the wear of tire studs during use (denoted $F_{re,\ i}$ in the article. $F_{14} + F_{15}$ is denoted $F_{losses\ u,\ i}$ in the article)
F_{16}	Tungsten in collected scrapped studded tires ($F_{16} + F_{17}$ is denoted $F_{to\ wm,\ i}$ in the article)
F_{17}	Tungsten in non-collected scrapped studded tires ($F_{16} + F_{17}$ is denoted $F_{to\ wm,\ i}$ in the article)
F_{18}	Tungsten in scrapped studded tires combusted in cement production
F_{19}	Tungsten in scrapped studded tires combusted in heat and power plants
F_{20}	Tungsten in scrapped studded tires used in granulation
F_{21}	Tungsten in scrapped studded tires used in construction works
F_{22}	Tungsten in scrapped studded tires reused for other purposes

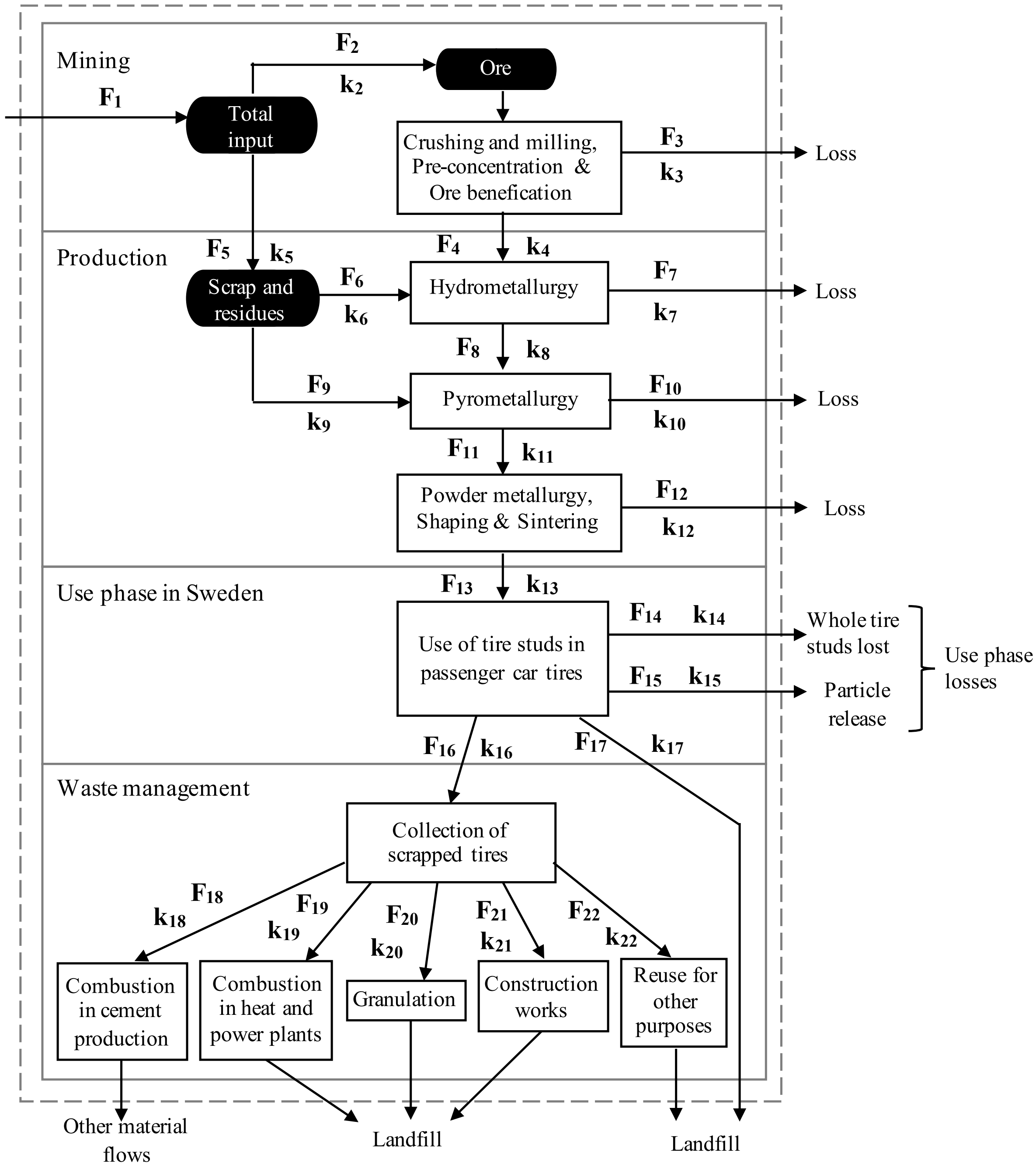

Figure S1. Parameters quantified in the tungsten flow calculations; tungsten flows (F) and transfer coefficients (k). The system boundary of the study is illustrated by the dashed line.

2.1. Estimation of tungsten flows in the use phase

The estimation of tungsten flows in the use phase are described in more detail here than in the article. A schematic picture of the use phase for tire studs in passenger cars is presented in Figure S2.

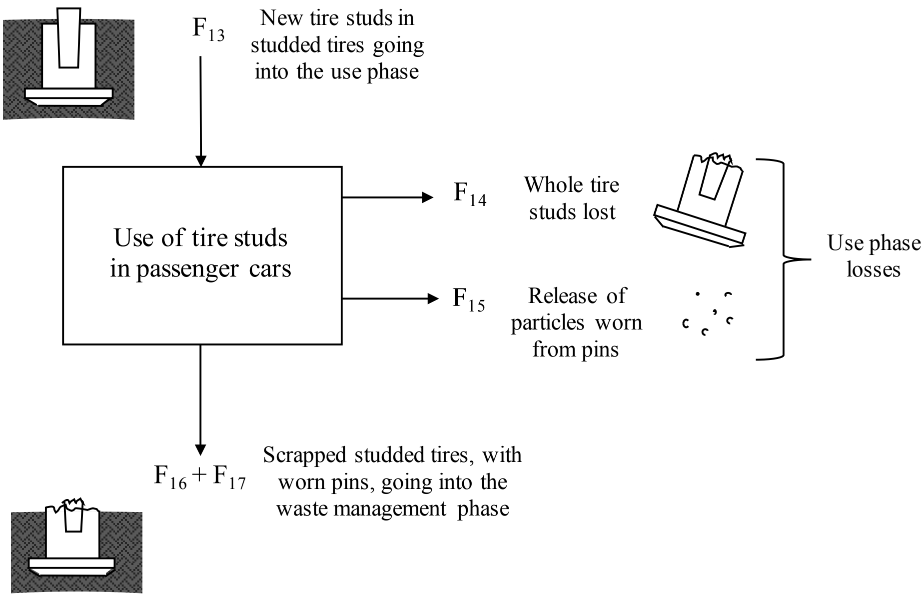

Figure S2. Schematic picture of the use phase for tire studs in studded passenger car tires.

The annual flow of tungsten in tire studs to the use phase in year *i*, F_{13} [kg/year], was estimated according to:

$$F_{13} = m_{pin} \times S_{pin,\ W} \times N_{ts} \times N_{tires} \times N_{new\ cars,\ i} \times S_i \qquad \text{(Eq.S1)}$$

where m_{pin} [kg] is the mass of a WC-Co pin, $S_{pin,\ W}$ [-] is the share of a pin that is tungsten, N_{ts} [-] is the number of studs per tire, N_{tires} [-] is the number of tires on a passenger car, $N_{new\ cars,\ i}$ [-] is the number of passenger cars that are new on the Swedish market in year *i* and S_i [-] is the share of passenger cars that had studded tires in the year *i*.

The use phase losses constitute both of whole tire studs lost from studded tires during their lifetime and particle release due to wear of the pins (Figure S2). Thus, the tire studs in scrapped studded tires going to the waste management phase are firstly reduced in number compared to N_{ts} since some whole tire studs are lost during the studded tires' lifetime and will therefore not reach the waste management phase. Secondly, the tire studs that do reach the waste management phase are worn. The flow of tungsten from the use phase going to the waste management phase, $(F_{16} + F_{17})$ [kg/year], was estimated according to:

$$(F_{16} + F_{17}) = F_{13} \times \underbrace{S_{wts}}_{\substack{\text{Share of tire studs}\\ \text{remaining in the}\\ \text{tires after use}}} \times \underbrace{(1 - S_{pin\ worn})}_{\substack{\text{Share of tungsten}\\ \text{remaining in these}\\ \text{tire studs after use}}} \quad \text{(Eq.S2)}$$

where S_{wts} [-] is the share of the number of tire studs that remains in the tire after use and $S_{pin\ worn}$ [-] is the share of a pin that is worn during the lifetime of studded tires.

Then, based on the assumption of steady state in the mass balance flow model, illustrated in Figure S1, the use phase losses of tungsten, $(F_{14} + F_{15})$ [kg/year], was estimated according to:

$$(F_{14} + F_{15}) = F_{13} - (F_{16} + F_{17}) \quad \text{(Eq.S3)}$$

The use phase losses are divided in two parts (Figure S2). The first part, namely the flow of tungsten in whole tire studs lost during use in year *i*, F_{14} [kg/year], was estimated according to:

$$F_{14} = F_{13} \times \underbrace{(1 - S_{wts})}_{\substack{\text{Share of whole tire}\\ \text{studs lost from the}\\ \text{tires after use}}} \times \underbrace{(1 - S_{wts\ lost\ worn} \times S_{pin\ worn})}_{\substack{\text{Share of the pins, in}\\ \text{whole tire studs lost, that}\\ \text{was not worn away}}} \quad \text{(Eq.S4)}$$

where $S_{wts\ lost\ worn}$ is the share of the total wear of a pin during the tire's lifetime that was worn away before the tire stud was lost whole from the studded tire.

The second part of the use phase losses, that is the release of particles in the use phase in year *i* from the wear of pins, F_{15} [kg/year], was estimated according to:

$$F_{15} = F_{13} \times (\underbrace{S_{wts} \times S_{pin\ worn}}_{\substack{\text{Wear originating from pins that}\\ \text{remain in the tires after use}}} + \underbrace{(1 - S_{wts}) \times S_{wts\ lost\ worn} \times S_{pin\ worn}}_{\substack{\text{Wear originating from pins}\\ \text{that were lost during use}}}) \quad \text{(Eq.S5)}$$

Thus, the particle release originates both from wear of the tire studs that remain on the tires during the tires' lifetime and from wear of the whole tire studs lost that took place before the tire studs were lost from the tire. The release of particles in the use phase, F_{15}, were also recalculated into WC-Co by dividing F_{15} with $S_{pin,\ W}$.

2.2. Estimation of tungsten flows upstream the use phase

Based on the estimation for F_{13}, the flows for F_{11}, F_{12}, and F_{10} can be calculated according to Eq. S6, S7 and S8.

$$F_{11} = \frac{F_{13}}{1 - S_{pom\ loss}} \quad \text{(Eq.S6)}$$

$$F_{12} = S_{pom\ loss} \times F_{11} \quad \text{(Eq.S7)}$$

$$F_{10} = S_{pym\ loss} \times \frac{F_{11}}{1 - S_{pym\ loss}} \quad \text{(Eq.S8)}$$

where $S_{pom\ loss}$ and $S_{pym\ loss}$ are the mass-based shares of tungsten lost in the powder metallurgy and pyrometallurgy processes, respectively. For input data, see Table S2.

In order to estimate the rest of the flows upstream the use phase, mass balances were applied. Creating mass balances over the pyrometallurgy process and over the hydrometallurgy process generated Eq. S9 and S10:

$$F_8 + F_9 = F_{10} + F_{11} \quad \text{(Eq.S9)}$$

$$F_4 + F_6 = F_7 + F_8 \quad \text{(Eq.S10)}$$

In order to be able to solve this system of equations, the number of unknowns in Eq. S9 and S10 had to be reduced to two parameters. The parameters F_4, F_6, F_7 and F_9 were therefore written in terms of the total input, F_1, in order to have the two parameters F_1 and F_8 as the only unknowns. This could be done due to knowledge of the relations described in Eq. S11, S12, S13, S14 and S15:

$$F_1 = F_2 + F_5 \quad \text{(Eq.S11)}$$

$$F_2 = S_{ti,\ ore} \times F_1 \quad \text{(Eq.S12)}$$

$$F_5 = S_{ti,\ scrap} \times F_1 \quad \text{(Eq.S13)}$$

$$F_6 = S_{scrap,\ cp} \times F_5 \quad \text{(Eq.S14)}$$

$$F_9 = S_{scrap,\, zp} \times F_5 \quad \text{(Eq.S15)}$$

where $S_{ti,\, ore}$ and $S_{ti,\, scrap}$ are the shares of the total input that comes from ore and scrap, respectively, and $S_{scrap,\, cp}$ and $S_{scrap,\, zp}$ are the shares of the scrap that is recycled through the chemical and zinc recycling process, respectively. Again, see Table S2 for input data.

Rewriting the parameters F_4, F_6, F_7 and F_9 using the parameter F_1 resulted in Eq. S16, S17, S18 and S19:

$$F_9 = S_{scrap,\, zp} \times S_{ti,\, scrap} \times F_1 \quad \text{(Eq.S16)}$$

$$F_6 = S_{scrap,\, cp} \times S_{ti,\, scrap} \times F_1 \quad \text{(Eq.S17)}$$

$$F_4 = (1 - S_{mining\ loss}) \times S_{ti,\, ore} \times F_1 \quad \text{(Eq.S18)}$$

$$F_7 = S_{hm\ loss} \times (F_6 + F_4) \quad \text{(Eq.S19)}$$

where $S_{mining\ loss}$ and $S_{hm\ loss}$ are the percentage losses of tungsten in the mining and hydrometallurgy processes, respectively (Table S2).

Furthermore, F_{11} and F_{10} in Eq. S9 are known from Eq. S6 and S8. At this point, F_1 and F_8 are the only unknowns in Eq. S9 and S10. If Eq. S9 is put into Eq. S10, this gives Eq. S20:

$$F_6 + F_4 = (F_{10} + F_{11} - F_9) + F_7 \quad \text{(Eq.S20)}$$

Then, if Eq. S16, S17, S18 and S19 are put into Eq. S20, this gives Eq. S21, where F_1 is the only unknown.

$$F_1 = (F_{10} + F_{11})/(S_{ti,\, ore} \times (1 - S_{hm\ loss}) \times (1 - S_{mining\ loss}) + S_{ti,\, scrap} \times (S_{scrap,\, cp} \times (1 - S_{hm\ loss}) + S_{scrap,\, zp})) \quad \text{(Eq.S21)}$$

Solving Eq. S21 gives a value for F_1. Then all the other flows upstream the use phase can be quantified by using Eq. S12 for F_2, Eq. S18 for F_4, Eq. S13 for F_5, Eq. S15 for F_9, and Eq. S14 for F_6. Eq. S19 and Eq. S9 can then be used to calculate F_7 and F_8, respectively. F_3 can be calculated according to:

$$F_3 = S_{mining\ loss} \times F_2 \quad \text{(Eq.S22)}$$

2.3. Estimation of tungsten flows downstream the use phase

The two flows going to the waste management phase can be estimated based on the estimation for ($F_{16} + F_{17}$), see Eq. S2, according to Eq. S23 and S24.

$$F_{16} = S_{scrap\ tires,\ c} \times (F_{16} + F_{17}) \quad \text{(Eq.S23)}$$

$$F_{17} = (1 - S_{scrap\ tires,\ c}) \times (F_{16} + F_{17}) \quad \text{(Eq.S24)}$$

where $S_{scrap\ tires,\ c}$ is the share of scrap tires that is collected, see Table S2 for input data. The flows of tungsten going into different types of treatment are shown in Eq. S25, S26, S27, S28 and S29, respectively.

$$F_{18} = S_{cement} \times F_{16} \quad \text{(Eq.S25)}$$

$$F_{19} = S_{plant} \times F_{16} \quad \text{(Eq.S26)}$$

$$F_{20} = S_{granulation} \times F_{16} \quad \text{(Eq.S27)}$$

$$F_{21} = S_{construction} \times F_{16} \quad \text{(Eq.S28)}$$

$$F_{22} = S_{reuse\ other} \times F_{16} \quad \text{(Eq.S29)}$$

where S_{cement}, S_{plant}, $S_{granulation}$, $S_{construction}$ and $S_{reuse\ other}$ are the shares of collected tires combusted in cement production, combusted in heat and power plants, used in granulation, applied in construction works and reused for other purposes, respectively (Table S2). The tungsten flows in the waste management phase were then categorized, see Section 3.1.5 and Section 4.1 in the article. F_{18} was categorized as lost in other material flows, the flows F_{17}, F_{19}, F_{20}, F_{21} and F_{22} were categorized as flows to landfill.

2.4. Resulting tungsten flows and transfer coefficients

Table S4. Resulting tungsten flows [ton/year] from the material flow calculations for the base case.

Parameter	Base case
F_1	38
F_2	29
F_3	7.3
F_4	22
F_5	9.2
F_6	4.6
F_7	1.1
F_8	25
F_9	4.6
F_{10}	0.30
F_{11}	30
F_{12}	0.30
F_{13}	29
F_{14}	3.8
F_{15}	20
F_{16}	5.7
F_{17}	0.15
F_{18}	0.97
F_{19}	1.5
F_{20}	1.9
F_{21}	0.69
F_{22}	0.57
Total landfill (F_{17}+F_{19}+F_{20}+F_{21}+F_{22})	4.9
Total loss in other material flows (F_{18})	0.97

Table S5. Resulting tungsten transfer coefficients for the base case. A cross indicates that the values are specific for the case of Sweden. For descriptions of and references to the parameters in the algebraic formulations, see Table S1 and S2. See also Figure S1.

Transfer coefficient	Algebraic formulation	Value	Specific for Sweden?
k_2	$S_{ti,\ ore}$	0.76	
k_3	$S_{mining\ loss}$	0.25	
k_4	$(1 - S_{mining\ loss})$	0.75	
k_5	$S_{ti,\ scrap}$	0.24	
k_6	$S_{scrap,\ cp}$	0.50	
k_7	$S_{hm\ loss}$	0.040	
k_8	$(1 - S_{hm\ loss})$	0.96	
k_9	$S_{scrap,\ zp}$	0.50	
k_{10}	$S_{pym\ loss}$	0.010	
k_{11}	$(1 - S_{pym\ loss})$	0.99	
k_{12}	$S_{pom\ loss}$	0.010	
k_{13}	$(1 - S_{pom\ loss})$	0.99	
k_{14}	$(1 - S_{wts}) \times (1 - S_{wts\ lost\ worn} \times S_{pin\ worn})$	0.13	X
k_{15}	$(S_{wts} \times S_{pin\ worn} + (1 - S_{wts}) \times S_{wts\ lost\ worn} \times S_{pin\ worn})$	0.67	X
k_{16}	$S_{scrap\ tires,\ c} \times S_{wts} \times (1 - S_{pin\ worn})$	0.19	X
k_{17}	$(1 - S_{scrap\ tires,\ c}) \times S_{wts} \times (1 - S_{pin\ worn})$	0.0050	X
k_{18}	S_{cement}	0.17	X
k_{19}	S_{plant}	0.27	X
k_{20}	$S_{granulation}$	0.34	X
k_{21}	$S_{construction}$	0.12	X
k_{22}	$S_{reuse\ other}$	0.10	X

3. Estimation of engineered nanomaterial release in Sweden

The data that was used in order to enable the comparison between estimated release of WC-Co nanoparticles from the wear of tire studs in this study and release of some engineered nanomaterials (ENMs) in various applications in Sweden are presented in this section. Data on release of ENMs in the European Union (EU) (Sun et al., 2014) and in Europe (Keller and Lazareva, 2014) are presented in Table S6. The data on ENM release in the EU in 2012 from Sun et al. (2014) was obtained by summing their estimated EU release to air, soil and surface water for each nanomaterial individually. The data on European ENM release in 2010 from Keller and Lazareva (2014) was obtained from their supplementary material by summing the European release to soil, water and air for each nanomaterial individually for their low and high release estimate, respectively.

EU and European ENM release were scaled using data on the gross domestic product (GDP) [current billion US$] in 2015 for Sweden, EU and Europe (World Bank, 2016). Based on limited data availability, the GDP for Europe had to be calculated. The GDP for Europe was obtained by adding the GDP for EU with the GDP for the European countries that were not members of the EU in 2015 (EU, 2016). GDP in 2015 was not available for Andorra, Liechtenstein, Monaco and San Marino. Therefore, the available GDP closest to the year of 2015 was chosen instead for these countries. The GDP for Andorra, Liechtenstein, Monaco and San Marino were available for the year of 2013, 2012, 2011 and 2008, respectively. The GDP for the Vatican City was not given but assumed to be negligible. In our calculations of the GDP for Europe, the GDP for the whole Russian Federation was included since the Russian Federation is included in Europe in the study by Keller and Lazareva (2014).

Table S6. Release of some engineered nanomaterials (ENMs) used in various applications [metric ton/year] in the European Union (EU) and Europe. The ENMs are silver (Ag), aluminum oxide (Al_2O_3), cerium oxide (CeO_2), carbon nanotubes (CNTs), copper (Cu), iron (Fe), fullerenes, nanoclays, silica dioxide (SiO_2), titanium dioxide (TiO_2) and zinc oxide (ZnO).

ENM	Release		
	In the EU (Sun et al., 2014)	In Europe (Keller and Lazareva, 2014)	
		Low estimate	High estimate
Ag	3	8	41
Al_2O_3	-	280	2 100
CeO_2	-	36	340
CNTs	5	15	100
Cu	-	0	10
Fe	-	600	3 000
Fullerenes	1	-	-
Nanoclays	-	110	390
SiO_2	-	330	2 500
TiO_2	4 400	3 400	10 000
ZnO	340	830	2 400

The estimated release of ENMs in EU and Europe in Table S6 were scaled to Swedish conditions using GDP**.** This is described in the article and presented here as well for clarity. In this way, the Swedish release of the engineered nanomaterial j in year i, $R_{j,\,Swe,\,i}$ [metric ton/year], was estimated using the data in Table S6 and the ratio between the Swedish GDP and the GDP for region k according to Eq. S30:

$$R_{j,\,Swe,\,i} = R_{j,\,k,\,i} \times \frac{GDP_{Swe,\,i}}{GDP_{k,\,i}} \qquad \text{(Eq.S30)}$$

where $R_{j,\,k,\,i}$ [metric ton/year] is the release of the ENM j in region k in year i, $GDP_{Swe,\,i}$ [current billion US$] is the gross domestic product for Sweden in year i, and $GDP_{k,\,i}$ [current billion US$] is the gross domestic product for region k in year i. The resulting GDP scaling factors used to estimate what share of the release of ENMs in the EU and Europe that can be ascribed to Sweden are presented in Table S7. Resulting estimated values for release of some ENMs in Sweden are presented in Table S8.

The estimates for Swedish ENM release in Table S8 were then used to compare with release of WC-Co nanoparticles from worn tire studs, $F_{15,\,NP}$ [kg WC-Co/year], which was estimated according to:

$$F_{15,\,NP} = (F_{15} / S_{pin,\,W}) \times S_{re,\,NP} \qquad \text{(Eq.S31)}$$

where F_{15} [kg/year] is the tungsten in particle release from pins during use, $S_{pin,\,W}$ [-] is the share of tungsten in a WC-Co pin and $S_{re,\,NP}$ [-] is the share of the use phase WC-Co particle release of WC-Co that is nanoparticles, see Table S2 for parameter data. A low and a high estimate was created for the release of WC-Co nanoparticles. The low and high estimate illustrate a low and a high release, respectively. The values used for the low and high WC-Co nanoparticle release estimates correspond to the low and high values in Table S2, respectively.

Table S7. Resulting GDP scaling factors [-] used to estimate what part of the European Union (EU) and European ENM release that can be attributed to Sweden following Sun et al. (2014) and Keller and Lazareva (2014), respectively.

Scaling factor	Value
$\frac{GDP_{Sweden}}{GDP_{EU}}$	0.030
$\frac{GDP_{Sweden}}{GDP_{Europe}}$	0.025

Table S8. Estimated release of some engineered nanomaterials (ENMs) [metric ton/year] in various applications in Sweden, based on estimated ENM release in the European Union (EU) and in Europe, and the estimated release of WC-Co nanoparticles from the wear of tire studs [metric ton/year] in this study. The ENMs are silver (Ag), aluminum oxide (Al_2O_3), cerium oxide (CeO_2), carbon nanotubes (CNTs), copper (Cu), iron (Fe), fullerenes, nanoclays, silica dioxide (SiO_2), titanium dioxide (TiO_2) and zinc oxide (ZnO). Data is also presented in Figure 3 in the article.

ENM	Estimated Swedish release		
	Based on EU data (Sun et al., 2014)	Based on European data (Keller and Lazareva, 2014)	
		Low estimate	High estimate
Ag	0.1	0.2	1
Al_2O_3	-	7.1	53
CeO_2	-	0.9	8.6
CNT	0.16	0.38	2.6
Cu	-	0	0.25
Fe	-	15	76
Fullerenes	0.036	-	-
Nanoclays	-	2.6	9.7
SiO_2	-	8.3	64
TiO_2	130	85	260
ZnO	10	21	61
Nanoparticle	WC-Co release (tire studs)		
	Base case	Low estimate	High estimate
WC-Co (tire studs)	1.8	0.21	6.1

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