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Tire Wear Monitoring Approach for Hotspot Identification in Road Deposited Sediments from a Metropolitan City in Germany

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Abstract: Plastic in the environment poses an increasing challenge. Microplastics, which include tire wear, enter the aquatic environment via different pathways, and increasing vehicle traffic leads to increased tire wear. This paper describes an approach for how inner-city tire wear hotspots can systematically be identified by sampling road-deposited sediments (RDS) by sweeping. Within the investigations herein described, six inner-city monitoring sites were sampled. The total masses of solids as well as the amount of styrene-butadiene rubber (SBR) representing Tire and Road Wear Particles (TRWP) were determined. It was shown that the sites differ significantly from each other with regard to SBR parts. The amount of SBR in the curve was on average eight times higher than in the slope, and in the area of the traffic lights, it was on average three times higher than in the slope. The RDS mass results also differ but with a factor of 2 for the curve and of 1.5 for the traffic light. The investigations and the corresponding results in this paper are unique, and the monitoring approach can be used in the future to derive and optimize sustainable measures in order to reduce the discharge of TRWP into the environment by road runoff.

Keywords: tire wear; microplastics; road sediments; sweeping; road runoff; hot spots; SBR

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1. Introduction

Plastic and its resulting microplastics, which include tire wear, are an increasing environmental challenge. Tire abrasion particles enter the aquatic environment through various pathways, and increasing vehicle traffic inevitably leads to increased tire abrasion [1]. Abrasion occurs as a product of friction between the tire and the road surface during normal vehicle use [2]. Both friction surfaces rub off, ultimately creating an agglomerate of the tire tread material and the road surface. Studies therefore also speak of tire-road wear particles or TRWP (Tire and Road Wear Particles) [2,3]. For the production of the tire, more than 200 raw materials are used [4]. The tread of the tire consists of rubber (e.g., styrene–butadiene rubber (SBR)) and filler (e.g., soot) as well as other ingredients [5,6]. Additives are used for the manufacturing process and performance [7]. Leaching can dissolve the substances from the particle, and represents an additional risk for aquatic ecosystems [8–10]. A link has already been established between salmon mortality and road runoff water due to the substance N-(1,3-dimethylbutyl)-N′-phenyl-1,4-benzenediamine (6PPD) and its quinone, and 6PPD is used in tires as an antioxidant [8].

In 2018, 360 million t of plastic were produced worldwide, with 61 million t in Europe [11]. Parts of this mass can enter the environment as microplastics. In addition, 15 million t of synthetic rubber and 29 million t of rubber were produced [12], and 5.1 million t of tires were produced in Europe [13]. In Germany, there are currently 47.7 million registered passenger cars [14]. The emission rates vary due to different influencing factors, which are discussed in Section 2. For example, for passenger cars and for lorries, respectively, 132 mg/km and 850 mg/km of emitted tire wear can be assumed in urban areas under normal conditions [15]. The total abrasion quantities in Germany can be calculated based on the annual mileage of the Kraftfahrt–Bundesamt (breakdown by vehicle type [16]) and the specific abrasion quantity per km [17].

This results in an estimated annual amount of 95,546–98,370 t for Germany, which corresponds to a specific population equivalent (PE) of 1148.9–1183.7 g/(PE*a) [18]. The released TRWPs are about 4–350 µm in size (100 µm in average), with a density range of 1.2–1.8 g/cm^3 [2,19]. For the entire EU, 450,000 t–1,300,000 t of tire abrasion can be assumed [20,21].

For Germany, the quantities generated can be divided into similar proportions between urban areas (29%), rural roads (33%), and highways (38%) [17]. In relation to the EU, it can be assumed that the larger share is related to both urban areas (40%) and rural roads (40%) rather than to highways (20%) [21]. The input of tire abrasion into the environment is balanced for Germany in Baensch-Baltruschat et al., and, according to this, 66–76% end up in the soil and 12–20% end up in surface water [17]. The airborne rate is specified as 5% [17,22,23].

Due to different drainage systems for road runoff, the majority of the input of tire wear to surface waters originates from urban areas [17]. From urban water management, microplastics and tire abrasion can generally enter limnic systems and oceans via three ways:

- Input of treated wastewater from wastewater treatment plants.
- Combined sewer overflows.
- Discharge of storm water from separate sewer systems.

In Germany, between 8120 and 16,820 t of tire abrasion are estimated to enter surface waters via separate sewer systems (46%), combined sewer overflows (11%), and via wastewater treatment plants (2%) as shown in Figure 1 [17].

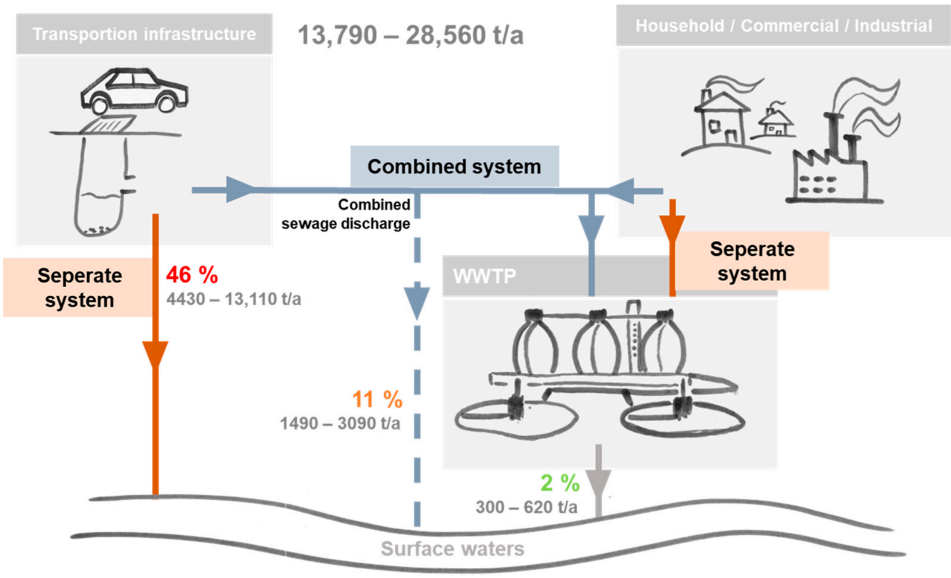

Figure 1. Tire wear pathways into surface waters. Calculation for Germany [17].

The estimated amounts of tire abrasion for the different rates into the water body have not yet been proved completely y the analytical data so far. The first investigations show for combined sewage the highest concentrations of microplastics for polyethylene (PE), but polystyrene (PS), polypropylene (PP), and styrene–butadiene rubber (SBR) could also be identified [24,25]. In Scheid et al. [24], SBR concentrations averaging 9–89 µg/L were detected in the storm sewer. In Unice et al. [26], extensive model calculations that consider transport phenomena and river hydrology are used. Extensive sensitivity analyses and probabilistic studies provide information on the reliability of the results. According to these, between 2–5% of the tire abrasion that is generated in the catchment area of the Seine river reaches the estuary [26]. Such estimates are hard to balance by field tests on this scale.

In Menguistu et al. [27], SBR concentrations in gullypots sediments were investigated, and a difference between traffic volumes was shown. Up to 150 mg tire wear/g sediment were measured [27].

In Kwak et al. [28], the impacts of the driving style and the topology were shown. A significant increase in emitted airborne particle mass concentration was measured, which was caused by higher lateral acceleration rates with higher velocities [28].

In general, data are lacking, and environmental measurements are needed to make reliable statements [29].

In order to be able to derive effective and sustainable measures on site and for all relevant stakeholders, road-related investigations to identify possible high emission locations (hotspots) are necessary. Since the input of tire wear into surface waters in urban areas is mainly from the area of the separate sewer system, hotspots should be identified by environmental samples, for which appropriate measures can be derived.

Therefore, the objective of this study is to describe an approach to monitor tire wear hotspots by analyzing RDS samples, which will be taken over a defined period of time on a relevant part of the road.

2. Materials and Methods

For the identification of potential hotspots, an understanding of the main influencing factors of tire-wear generation is essential. From the experience of an external panel of experts, the abrasion factors for a passenger car tire have been estimated, as shown in Figure 2. The analysis shows that the topology and the driving behavior of motorists are the greatest influencing factors with regards to tire abrasion [30]. Similar results can be found in the TyreWearMapping report. When modelling the physical factors influencing the tire in connection with the German road network, the model calculated about 80% of the tire wear at intersections and curves [31].

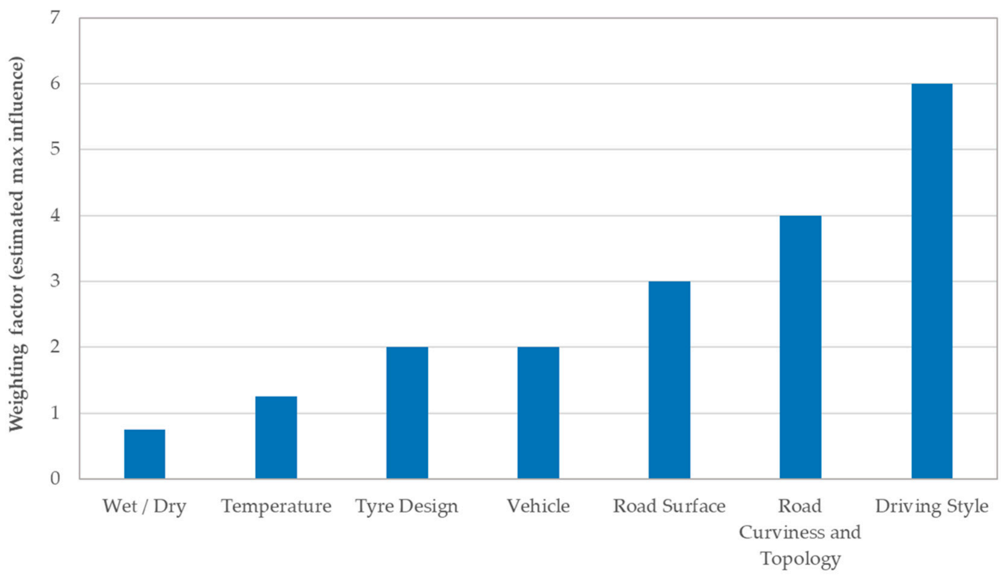

Figure 2. Influencing factors on tire wear [30].

On the part of the road surface, it can be assumed that the microstructure has an effect on abrasion. The contact surfaces and the corresponding tangential stresses are relevant here [32]. The vehicle and tire design take into account the targeted tire load [30]. In tire wear tests, driving stability, driving comfort, and steering behavior, as well as driving safety, durability, and economy, are all factors that are considered, among others [32]. The influencing factors of temperature and wet/dry define the ambient temperature and the proportion of the wet road [30]. Since driving behavior is also often linked to the topology of the road, it is difficult to consider it separately. It has been assumed that acceleration behavior is most likely to occur at intersections with traffic lights. Further increased stress situations for the friction process between tire and road are expected at curves, roundabouts, and slopes. As a reference to increased stress situations, a straight road section with an expected constant speed has been selected in order to consider the tire-wear emission with a "neutral" driving style. The measuring locations were chosen as close to each other as possible in order to ensure a similar traffic volume. To verify the methodology, further measurements were made at a paved public location in a park where no tire wear from vehicles is expected because access is only possible via stairs. In the context of this work, the results for the systematic 24 h sweeping samples of the measuring points shown below are presented. All of the selected sampling sites are located near the Humboldthain Park in the Wedding district of Berlin.

The area in which the sites are located is an urban residential area with various services of general interest and parks. The buildings usually have five floors, and there are tree grates along most of the streets. A distinctive feature of the sampling spots, labelled "straight", "traffic light", and "curve", is the rail line that runs along the eastern side below the street, but the impact of this could not be investigated in this piece of research. The streets where the measurement sites are located have a roof profile, and they thus drain to both sides of the street, which is common for the Berlin metropole region. The samples were taken on one side of the road. The roundabout, as shown in Figure 3, connects four roads, and it has a section where the road is straight rather than curved. The details of the sampling locations are shown in Table 1.

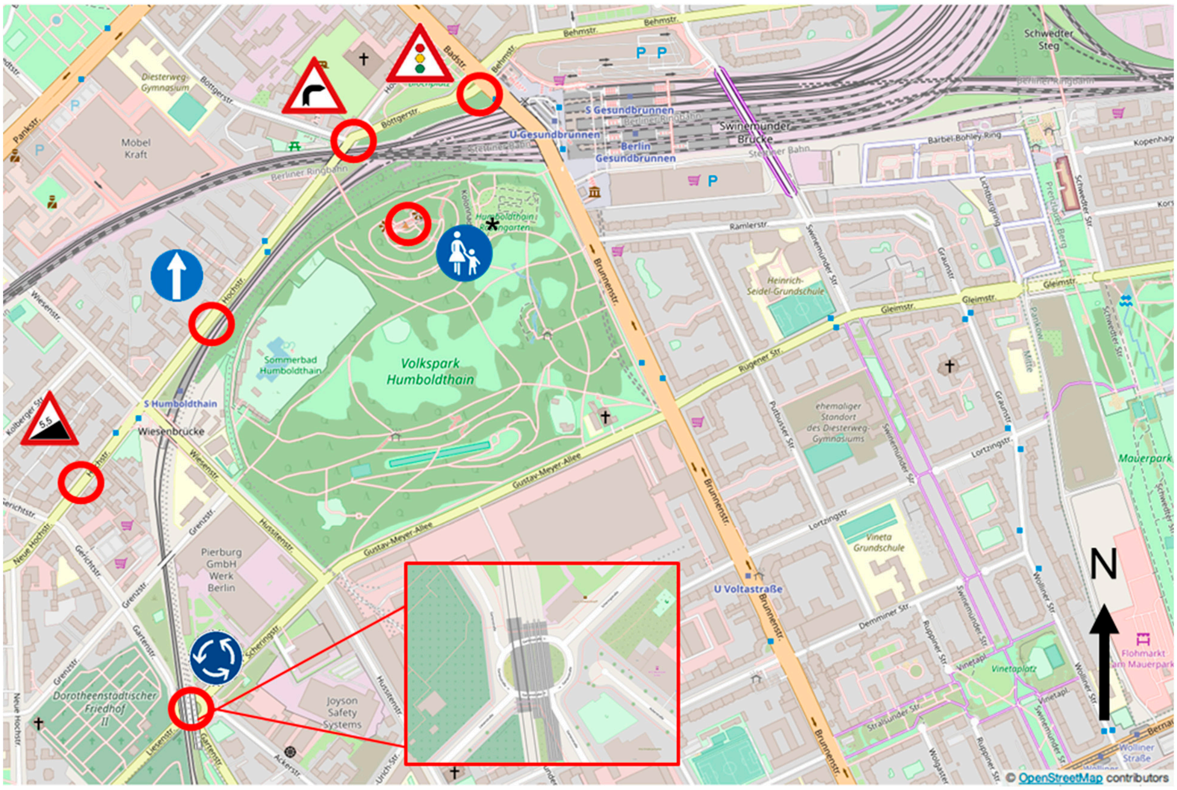

Figure 3. Selected sampling and reference (*) locations (© OpenStreetMap [33]).

Table 1. Sampling locations details.

Sampling Location		Road Width [m]	Curb Height [m]	Walkway Width [m]	Slope in Driving Direction	Overlay by Tree	Boundary to Tree Slice
	Straight	10.5	0.12	7.7	0.9%	10%	Yes
	Traffic lights	8.8	0.13	3.9	1.0%	70%	Yes
	Curve (r = 65 m)	11.3	0.04	3.8	0.8%	0%	No
	Slope	11.4	0.03	7.7	3.2%	50%	Yes
	Roundabout	8.4	0.13	6.4	2.2%	0%	No

2.1. Road-Deposited Sediment Sampling by Sweeping

The road-deposited sediment (RDS) sampling by sweeping was preferred over sampling with a vacuum cleaner for reasons of practicality in the field. For sweep sampling, a hall broom made of horsehair with a width of 80 cm (Figure 4) was used. The RDS was swept steadily from both ends of the sampling area into its center. Based on the experience of a street cleaning company, a corresponding operating technique was derived: the broom has to be operated with short powerful strokes instead of long soft strokes. Thus, it was expected that we would also be able to extract material from the interstices of the rock matrix. The movements of the "sweeping strokes" were carried out according to the principle "three steps forward, two steps back". To collect the RDS, a hand brush made of horsehair (Figure 4) and a metal dustpan was used and placed in a sample jar. The entire surface was then cleaned again with the hand sweeper, and the dustpan was permanently guided in front of the broom in such a way that material mobilized by the RDS reached the dustpan directly. The material obtained was then transferred from the sweeping plate into a glass sample container. (During the transferring process, care must be taken to ensure that no sample material is lost from the sweeper plate due to wind from passing vehicles.)

Figure 4. Hall broom with horsehair (**left**) and hand brush with dustpan (**center**) and examples of the RDS samples ((**right**): (a) 20–50 µm, (b) 50–100 µm and (c) 100–500 µm).

Recovery rates for the described RDS sweep sampling of 90% for the fraction 20–500 µm could be determined, and they were evaluated at the edge of the pavement with a defined test material for the asphalt layer that was sampled.

The analysis of RDS from the roadway offers the possibility of determining the TRWP generated under real conditions over a defined period of time for a defined distance considering the actual number of motor vehicles driven. These values for the fraction 20–500 µm describe the main corresponding input potential for TRWP, which can be washed off the roadway during a rain event.

2.2. Investigation of the Particles Distribution across the Road

It has already been shown in previous investigations that the largest proportion of RDS is deposited in the edge area of the road. Pitt et al. [34] found 90% of the solids in the 0.3 m wide edge area of the road, and by investigating over half of a 5 m wide road cross section, Grottker [35] found 96% of the solids within 0.5 m to the curb.

These findings are vital for the study of TRWP on urban road surfaces. It is assumed that TRWPs are part of the RDS, and that they accumulate mainly in the peripheral area of the road. For the RDS distribution as well as for the corresponding SBR accumulation, cross sweeps were carried out over the road cross-section in the study area at the "straight" location. The investigations were carried out in order to verify whether the distribution of TRWP follows the same analogy as the RDS does. The results were important in order to define the relevant tracks of the lane to sample TRWP.

In order to be able to take samples on the entire lane, the lane must be closed for the time of sample taking. By identifying and confirming the relevant tracks for TRWP, the most practical way of sampling could be defined.

For investigations, the 4.1 m wide roadway, including the bike lane, was divided into five sections, each 0.8 m wide, at the "straight" location. Figure 5 shows the test setup. Samples were obtained during the day on lanes 1 to 5 over a length of 15 m after 24 h each on two consecutive working days in May and then on one working day in July. The length of the sample areas of 15.0 m was chosen in order to ensure that sufficiently large masses of solids were picked up. The surface was cleaned 24 h before by a corresponding basic cleaning according to the same sweeping pattern, so that the samples were exposed to the same external influences.

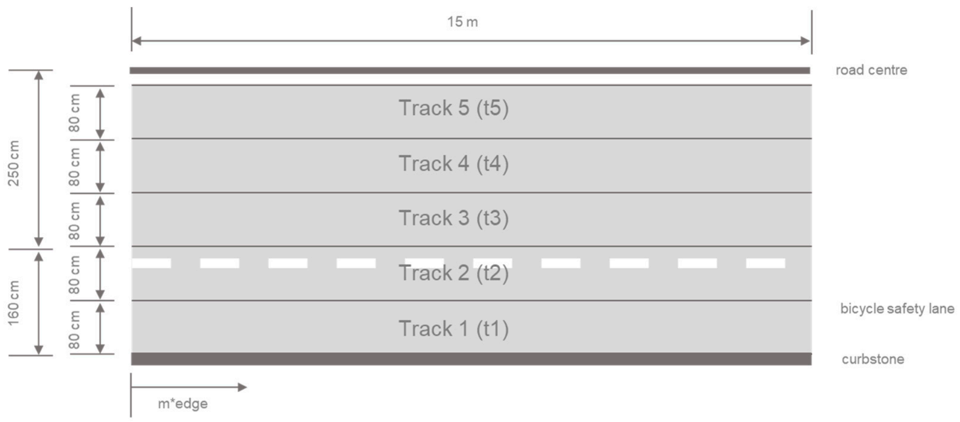

Figure 5. Subdivision of the sampling location "Straight".

2.3. 24 h Sampling

With the findings of the RDS particle distribution investigations across the road, the dimensions of the detailed studies of the hotspots were adjusted. The sampling time interval should be as short as possible or as long as necessary in order to minimize external influences and, at the same time, to represent the traffic pattern. Accordingly, a time interval of 24 h was chosen. The areas sampled for over 24 h have a length of 6.0 m and a width of 1.6 m parallel to the driving direction. The width of the surface is divided into two areas of 0.8 m each—track 1, which is adjacent to the outer road wheel, and track 2, which is adjacent to the outer road in the direction of the center of the road (Figure 6).

The 24 h sampling is preceded by a corresponding basic cleaning according to the same sweeping pattern. This ensures that the sample of the 24 h sampling consists only of particles that have arisen in the 24 h since the previous cleaning. The samples can be taken all over the year within a dry period.

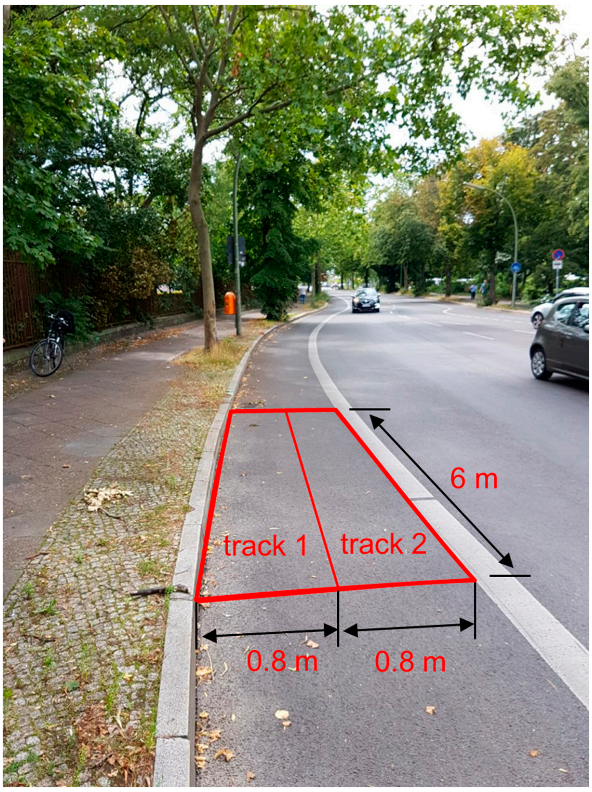

Figure 6. Sampling area: sweeping surface in the road space with characteristic dimensions.

Traffic Counting

The traffic volume is an important parameter for the investigation and comparability of the volume of solid matter and the amount of TRWP on road surfaces. By selecting the measurement sites, it was considered that the annual average daily traffic (AADT) is comparable. In order to determine the real traffic (average actual daily traffic) within a 24 h sampling campaign, radar measuring device "traffic counters" were used from Wavetec (Figure 7).

Figure 7. Traffic counting with radar meter—Wavetec.

The radar meter makes it possible to record the time, the vehicle length, and the speed of passing vehicles on a specific road cross-section. With the parameter vehicle length, different vehicle types can be identified: heavy-duty vehicle (HDV), low-duty vehicle (LDV), and bicycles. For the analysis of the data, a separation limit of 2.3 m and a speed of 26 km/h were applied in order to distinguish motor vehicles from cyclists. Vehicles less than 7.0 m in length were evaluated as LDV. The remaining vehicles were evaluated as HDV.

The measuring devices were set up at the sweeping areas in order to record the traffic on the respective side of the road. In order to detect the vehicles with the radar meter, they must pass the meter on a straight section of the road.

2.4. Analysitcs and Evaluation

The determination of the tire abrasion content from all of the described environmental samples was carried out externally according to ISO/TS 21396 [36] using pyrolysis/GC-MS [32]. For chemical analysis and the detection of tire wear, the marker SBR-BR was chosen. For fractionating the sample, a sieve cascade of four sieves with mesh sizes of 500 µm, 100 µm, 50 µm, and 20 µm was installed on an analytical sieve shaker twice for 5 min with a 2 min break in between [37]. Due to standard regulations for sieving of a dry sample with standardized sieves, the lower cut off limit was 20 µm [38]. With the size spectrum of 20–500 µm, more than 90% of the expected TRWP could be described [2].

The differences of the SBR and the RDS masses among the sampling locations were tested using one-way analysis of variance (ANOVA) followed by a Tukey pairwise comparison test in order to identify the relevant sampling tracks (Figure 5) and the inner-city hotspots (Figure 3).

3. Results and Discussion

This section describes in four steps the distribution of RDS and SBR across the road. For the six regularly sampled sites, both the RDS and the SBR values are presented and hotspots are identified. The representation of the AADT serves the comparability of the measuring points.

3.1. Investigation of the Particles Distribution across the Road

The results of the cross sweeps for the relative mass distribution of all solid particles within the RDS of the fraction sieved 20–500 µm are shown in Figure 8. On average, a total mass of 68.9 g RDS was determined for track 1–5 for the fraction 20–500 µm. To find out whether the TRWPs are distributed analogously to the RDS across the pavement cross-section, the rubber content was measured in the respective fraction. For this purpose, styrene-butadiene rubber (SBR) was chosen as the marker. On average, an SBR quantity of 147.5 mg was detected for tracks 1–5 for the fraction 20–500 µm. This investigation was repeated on different days, and was conducted three times in total ($n = 3$).

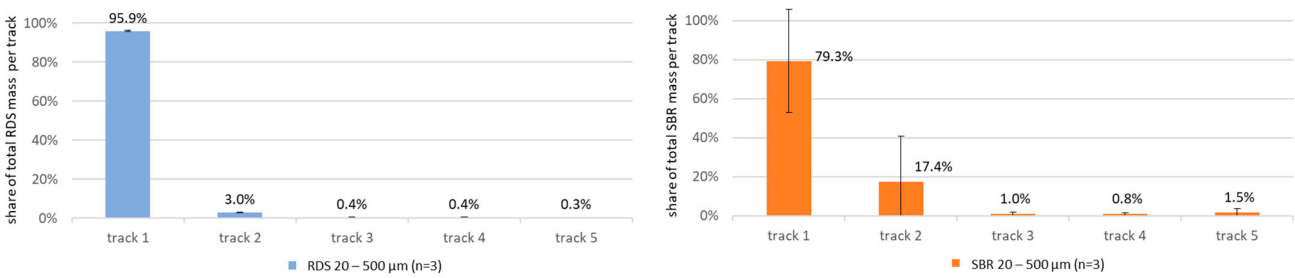

Figure 8. Mass distributions of RDS and SBR for the roadway cross-section.

The RDS results show a significant difference of track 1 to tracks 2–5 (pairwise *t*-test ($p < 0.0001$) (Table S1)). The results show that most of the RDS are located on track 1 (95.9 m%) and track 2 (3.0 m%). The low standard deviations of the RDS mass distribution on all tracks shows the homogeneity of the results.

The SBR results show a significant difference of track 1 compared to tracks 2–5 (pairwise *t*-test ($p < 0.05$) (Table S2)). The mass distribution of SBR is less constant within the three measurement days, as evidenced by the high standard deviations of track 1 (26.5 m%)

and track 2 (23.5 m%). Nevertheless, most of the SBR is deposited in track 1 (79.3 m%) and track 2 (17.4 m%). The measurements clearly show that in terms of RDS masses and in order to determine SBR contents in the inner-city area, it is sufficiently representative to sample 1.6 m (track 1 and 2) from the curb to the center of the roadway. The RDS results can also be confirmed with reference to the literature [39]. The distribution of the SBR across the lane width is described here for the first time. For the sampling of RDS, the sampling of track 1 would be sufficient, but for the consideration of SBR, sampling of tracks 1 and 2 is recommended.

3.2. 24 h Sampling RDS

The total masses by fraction from all 24 h samplings (*n*) per investigation site are shown in Figure 9. The RDS masses per track have been determined as described in the methodology section, and they are specifically shown in meters along the edge (Figure 5). The sampling locations were determined with the ANOVA and Tukey test. No significant differences are found here (Table S3).

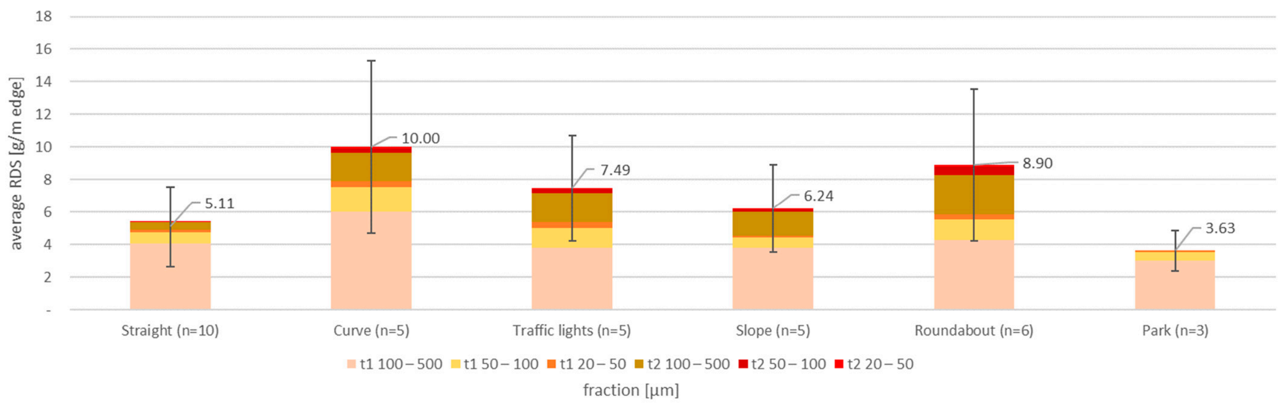

Figure 9. RDS results for the sampling locations for track 1 (t1) and track 2 (t2).

The values shown can be converted to g/m^2 using a factor of 1.2, but for reasons of consistency with the sampling procedure, the value m*edge is deliberately chosen. In this way, the distribution along the lane is underlined. The values of RDS vary from 5.11 g/m*edge at the straight to 10.00 g/m*edge at the curve. The differences between "straight", "traffic lights", and "slope" can be explained by the different boundary conditions, as mentioned in Table 1, at the sites. Leaves from trees and solids from the tree slice can potentially end up in the sampling area. There is no direct overlay by trees at the curve and the roundabout, admittedly, but the surrounding area does have many trees and sandy beds, which leads to comparable boundary conditions. The sampling spot in the park was not influenced by vehicle traffic at all. Approximately 10% of the area is covered by trees, similar to the measurement site "straight", and the immediate surroundings are green areas.

The total masses for all sampling locations consist mainly of the coarse fraction of 100–500 µm. This conclusion corresponds to the expectation from the literature [40,41]. The roadside sampling spots are in similar ranges. For the locations "roundabout" and "curve", the values are increased compared to the locations "straight" and "slope". The influencing parameters on tire wear are not reflected in the RDS results of the sampled sites, and they do not appear to have any significant quantitative or qualitative influence on the RDS characteristics. For this reason, additional analysis of the SBR content is essential for monitoring purposes.

3.3. 24 h Sampling SBR

As described in Section 2.4, the mass of SBR was determined for all of the sampling sites with repeated sampling (*n*).

The masses of SBR/m*edge determined in Figure 10 show clear differences within the sampling spots. The SBR results are significantly higher at the curve site in pair-wise comparisons to the sites "straight", "slope", and "roundabout" (one-way ANOVA Tukey Test, 95% confidence level (Table S4)). As expected, the mean SBR value of the curve is the highest at 34.43 ± 36.06 mg/m*edge. It is assumed that the higher lateral forces lead to increased emergence. The high standard deviation results from a single value (67.3 mg/m*edge) in the fraction 100–500 µm of track 2. The influence of a single vehicle is suspected, since there are no abnormalities in traffic load, vehicle types, or the sampling protocol. The sampling site of the traffic lights provides the second highest SBR value of 16.03 ± 8.12 mg/m*edge, which is probably also due to acceleration when starting as well as negative acceleration when braking. The "straight" road section 5.46 ± 4.21 mg/m*edge and the "slope" 4.50 ± 3.89 mg/m*edge show lower values but are in the same size range. The values do not correspond to any particular stress, and the driving situation was predominantly fluent. The roundabout 0.49 ± 0.45 mg/m*edge has, contrary to expectations, the lowest SBR results values within the five road sites. In order to be able to carry out the traffic count, the straight section of the roundabout had to be selected (see Section 2.3 above). It is assumed that the road layout at the sampling point and the relatively low speed led to low lateral forces, which affect the measured values. For a detailed description of a roundabout, several measuring points within the roundabout should be considered for future measurements. In the fraction 100–500 µm, most SBR was measured at all traffic locations. As expected, no SBR was found at the park sampling location because no vehicles operate there.

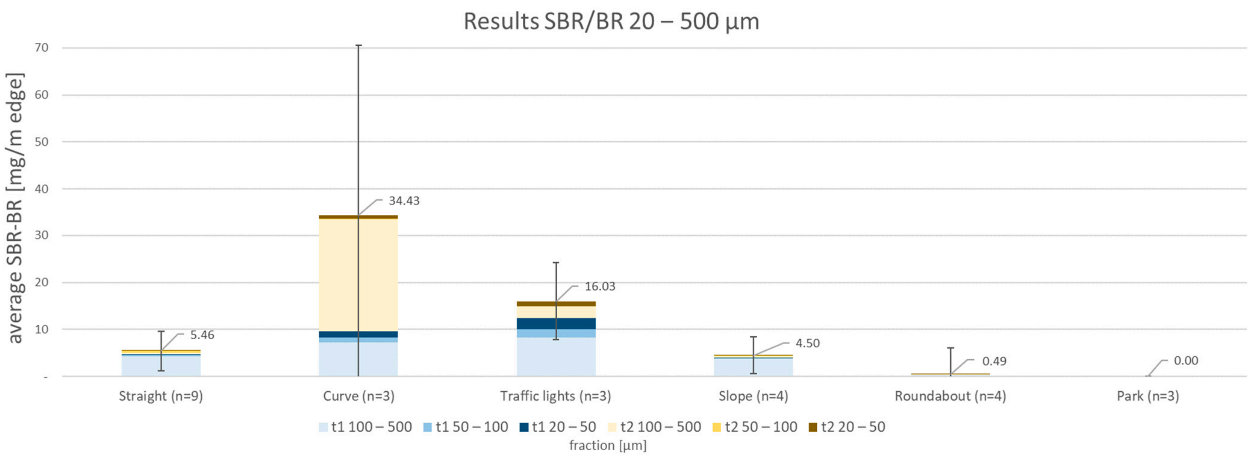

Figure 10. SBR results for the sampling locations for track 1 (t1) and track 2 (t2).

Despite the strongly fluctuating measured values, it can be seen that the locations "curve" and "traffic lights" with a higher load resulting from the driving situation show significantly more SBR than the locations "slope" and "straight", and they can therefore be classified as hotspots. The "Tyre Wear Mapping" report, which identifies curves and intersections as the largest emission location by modeling the physical parameters, came to a similar conclusion [31].

The results shown here are generally in line with expectations. The influencing factors mentioned in Figure 2 are reflected in the results. For the first time, it is possible to identify the magnitudes of different emission hotspots. These findings are an important element in the targeted and efficient selection of sustainable measures to reduce microplastics from tires entering into the environment.

These have to be selected specifically for the location. For the "curve", for example, this could mean that the maximum permitted speeds should be reduced. Additionally, when planning new roads, a curve radius as large as possible can help. For traffic lights, a reduction of the acceleration events by "stop and go" would be an additional solution.

Furthermore, treating the road runoff in the gully using retrofit filter systems is another way to reduce the input into the environment as quickly as possible. The filter systems can be supplemented very well by targeted road cleaning.

3.4. Traffic Counting

In order to exclude the influence of traffic volume and vehicle type and thereby ensure the comparability of the sites, the traffic was counted.

Regarding the main results, the average actual daily traffic for passenger cars (LDV) and their average travel speeds are shown in Table 2. For the measuring points, comparable traffic amounts of 5836–6308 and average speeds of 40–41 km/h can be observed. Only for the roundabout was a lesser speed of 25 km/h determined. The traffic amount of 6262 for the traffic lights was detected for the approaching vehicles 50 m beforehand in order to be able to reliably count the passing vehicles. The average speed cannot be transferred to the sampling point at the traffic lights because vehicles drive through, brake, or stop there.

Table 2. Average actual daily traffic/vehicle type: LDV (<7 m) HDV (>7 m) (SD = standard deviation).

Sampling Location		Vehicle Type	Num. [vehicle/day]	SD [vehicle/day]	Share	Ø-Speed [km/h]	SD [km/h]
	Straight	Bicycle	886	113	13%	15	4
		LDV	5932	320	84%	40	6
		HDV	246	41	3%	40	6
	Traffic lights	Bicycle	1086	52	14%	16	4
		LDV	6262	221	82%	40	6
		HDV	272	35	4%	40	6
	Curve	Bicycle	1012	52	15%	15	3
		LDV	5510	139	81%	24	3
		HDV	275	41	4%	24	3
	Slope	Bicycle	987	53	14%	13	4
		LDV	5836	110	83%	41	6
		HDV	212	9	3%	41	6
	Roundabout	Bicycle	1216	45	15%	16	2
		LDV	6308	211	78%	25	5
		HDV	596	5	7%	25	5

According to Bäumer et al. [42], the share of LDVs in urban motorised traffic in Germany is 95%. The results of the following table confirm the range (95–96%) for motorised traffic. Therefore, the sampling locations are representative for a German metropolitan region.

The share of trucks and bicycles is very low. It is assumed that the relevant quantities result from cars. Although the emission rate of the HDV is higher, the dominant share is due to the traffic volume of the LDV.

4. Conclusions

Tire wear is one of the largest sources of microplastics. The traffic and transport processes on the roads play an important role in terms of society's needs. Even by increasing e-mobility currently and in the future, the emission of tire abrasion cannot be properly solved. In order to derive sustainable solutions over the entire use phase of a tire, intensive interdisciplinary cooperation between all of the relevant stakeholders is required. Through a systematic hotspot approach, both preventive and acute sustainable solution concepts can be implemented and tested for effectiveness. Within the monitoring approach, dry environmental samples of RDS with a defined sampling protocol and systematic 24 h samples with automatic traffic counting could be successfully implemented. A basic cleaning of the sampling areas according to the same pattern has to be conducted before this can take place, though. It can be assumed that with the sampling of the edge area, the total mass of the RDS with up to 98.9%, as well as the accumulating amount of TRWP with up to 96.7%, can be sampled representatively.

Emission differences for TRWP could be determined by comparing different stress situation points, such as the straight, the slope, the curve, and the traffic lights, and it could be shown that the areas of the curve and the traffic lights describe inner-city TRWP hotspots.

The parameters influencing tire wear, which were selected on the basis of the various sampling sites, correlate with the SBR amount. A correlation of RDS and SBR for the hotspots is not possible. Therefore, SBR determinations must be made specifically for monitoring in the future.

The particles that are potentially washed off by the road runoff and that are often directly flushed into the corresponding surface waters can be sampled in the future by defined 24 h road sediment sampling. With the described procedure, inner-city hotspots for tire abrasion can successively be identified. Through further investigations and an increasingly growing database, it should also be possible to reduce the large standard deviation of the SBR values in the future. Possible reasons for the deviations could be the drifting of tire abrasion particles from the study area. This could be caused by individual special vehicles that lead to particularly high amounts of turbulence for a short time, such as agricultural machinery or construction vehicles. Unusually aggressive driving by individual drivers could also lead to particularly high readings. Here, unnecessarily strong acceleration probably plays just as much of a role as hazard braking. These correlations cannot be derived from the measured values collected in this study. To describe individual load scenarios, individual tests should be carried out on defined test tracks. These results could be used in the future to derive appropriate correction factors.

Frequencies of emitted tire abrasion could be determined for different curve radii and intersection situations based on the described sweep sampling method. The findings can be used, for example, to control the targeted deployment of street sweepers at the relevant hotspots shortly before a rain event or to enable the selection of suitable decentralized filters for cleaning street runoff water. In addition, data obtained in the described manner can be stored in corresponding digital planning tools in order to take emissions into account in urban planning.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151512029/s1.

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