Research and Innovation action

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LEON-T

Low particle Emissions and lOw Noise Tyres

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1. Contents

2. Executive summary

The goal of **Work Package 6 (WP6)** is to synthesise the knowledge gained during the project's experimental activities into potential new policies and regulations and to evaluate their possible future impact for the public health and wellbeing of citizens, as well as the social acceptance of the economic impacts that could derive from the new policies and regulations. Possible future policy scenarios include tyre airborne particle emissions (**Deliverable 6.1**), microplastics emissions (**Deliverable 6.2**), and tyre noise emissions (**Deliverable 6.3**). The final executive summary (**Deliverable 6.4)** gathers the most relevant policy recommendations in all the three topics. More specifically, **Deliverable 6.1** evaluates future new policies and mitigation strategies on tyre wear particle emissions. The three scenarios considered were: (i) the **baseline scenario** investigating the possible evolution of the problem assuming a no policy change scenario ; (ii) the **second scenario** examining the feasibility of emission regulation similar to that of exhaust emissions, i.e. particulate matter (PM); (iii) the **third scenario** examining the possibility to control tyre wear particle emissions through tyre abrasion rate. For both the second (PM) and third (abrasion) scenarios three policy cases were examined: reduction 10%, 20% and 30%.

In this study we conducted a cost-benefit analysis to evaluate the costs and savings of PM or abrasion rate reductions.
A basic assumption was that C1 tyres are fitted to passenger cars (PCs), C2 tyres to light-commercial vehicles (LCVs), and C3 tyres to heavy-duty vehicles (HDVs). We assumed a 0.7% annual fleet stock increase, 3.2% increase of the electrified vehicles, 11,500 km, 20,000 km, and 100,000 km annual mileage for PCs, LCVs, and HDVs respectively. The electrified PCs were considered to be 20% heavier than the conventional PCs, with a direct proportional impact on the emissions. Electrified LCVs and HDVs were considered 15 and 5%, respectively, heavier from their conventional counterparts. The emission factors were taken at the lower edge of the range given in a recent review. For PCs we considered an abrasion rate (AR) of 95.7 mg/km, 2 times higher AR for LCVs and 8 times higher AR for HDVs. The cost burden of the tyre wear as PM was taken from the 'Handbook of costs'. As there is no such cost for microplastics (sizes < 5 mm), we searched the literature for cost estimations of plastics and we considered the minimum value (7.2 EUR_{2025}/kg) as cost of microplastics.
In our reference baseline scenario the fleet from approximately 255 million vehicles in 2025 reached 352 million vehicles in 2050, of which 307 million were PCs and 37 million LCVs. The electrified PCs reached 91.5% in 2050, 87.3% for LCVs and 82% for HDVs. The tyre wear mass from 867 kt in 2016, increased to 985 kt in 2025 and 1270 kt in 2050. PCs contribute to tyre pollution 32% (±1%) and HDVs 56% (±1%).
Scenario 2 examined PM and Scenario 3 abrasion. One 'Policy' case assumed a basic 10% reduction of all emission factors following the gradual Euro 7 implementing dates for C1, C2 and C3 tyres. Such reduction can be achieved by various methods; however,

this study made no assumption on the final decision on the abrasion limits linked with Euro 7. These will be the object of a full evaluation following a market assessment, which is due by end of 2024 for C1 tyres. Variations of this basic scenario to test other hypotheses (with 20% and 30% reduction of emissions factors) were also analysed. The basic 10% scenario resulted in 7% less mass from abrasion until 2050 (2,115 kt less mass). The cost savings from reduced tyre abrasion were estimated to be around 11,000 million EUR; 1,700 million EUR from less PM_{10} and 3,400 million EUR from less $PM_{2.5}$. The combined benefit was 15,000 million EUR (excluding overlapping size regions). Taking into account testing and administrative, research and development costs, the net benefit was still a significant 14,000 million EUR. Assuming that the high emitting tyres would increase their price due to production costs (2% per tyre), the net benefit for the 2025-2050 period would be halved (7,300 million EUR). The positive impact will start to be visible between 2029 to 2032 (depending on the assumed costs) and will reach the maximum per year in 2035.

3. List of abbreviations and acronyms

Abbreviation	Definition
ACEA	European Automobile Manufacturers' Association
ADAC	General German automobile club
AR	Abrasion rate
B	Burden
CBA	Cost benefit analysis
COPERT	Calculations of emissions from road transport
D	Damage cost
EF	Emission factor
ETRMA	European tyre & rubber manufacturers association
EU	European Union
f	Inflation rate
HDV	Heavy duty vehicle
ICE	Internal combustion engine
j	Vehicle category (PC, LCV, HDV)
LCV	Light commercial vehicle
M	Mileage (per year)
MRO	Mass in running order
N	Number of vehicles
p	Pollutant ($PM_{2.5}$, PM_{10} or abrasion)
P	Percentage of pollutant in total wear
PC	Passenger car
PEMS	Portable emissions measurement system
PM	Particulate matter
r	Discount rate
R&D	Research and development
SIBYL	Database with vehicle information projections
TE	Total emissions released
UNECE	United Nations European Commission for Europe
UTAC	Union technique de l'automobile, du motocycle et du cycle
V	Value
WLTC	Worldwide light vehicles harmonized test cycle
WP	Work package
xEV	Electrified vehicle (battery and hybrid vehicles)

y	Reference year (2025)
Y	Incremental year (1 for 2026)

4. Introduction

The goal of **Work Package 6 (WP6)** is to synthesise the knowledge gained during the project's experimental activities into potential new policies and regulations and to evaluate their possible future impact for the public health and wellbeing of citizens, as well as the social acceptance of the economic impacts that could derive from the new policies and regulations. Possible future policy scenarios include tyre airborne particle emissions (**Deliverable 6.1**), microplastics emissions (**Deliverable 6.2**), and tyre noise emissions (**Deliverable 6.3**). The final executive summary (**Deliverable 6.4)** gathers the most relevant policy recommendations in all the three topics. This outcome may contribute to identifying guidelines for future policies and envisaging specific actions to mitigate tyre emissions. All tasks build on leading projects in the space of research, policy and regulations on the environmental and human health aspects of the tyre industry.

4.1. Overview of Task 6.1

Task 6.1 included: (i) definition of possible future policy scenarios regarding tyre wear particle emissions; (ii) cost benefit analysis and evaluation of their impact to the public health and well-being of citizens.

Three scenarios were considered in this Task 6.1 for tyre wear particle emissions. The **baseline scenario** investigated the possible evolution of the problem assuming a no policy change scenario. The **second scenario** examined the feasibility of imposing tyre emission regulation in a framework similar to that of exhaust emissions, i.e. particulate matter (PM). Finally, the **third scenario** examined the possibility to control tyre wear particle emissions through tyre abrasion rate.

The information from WP2 (Task 2.1) and the literature related to the assessment and characterisation of tyre particle emissions under different driving conditions were collected. Derived PM_{10} and $PM_{2.5}$ emission factors as well as possible adverse health effects of transformed species were studied to understand and define the magnitude of the problem. This information was used as input for all three policy scenarios. Input from WP2 (Task 2.3) related to the development of suitable methodologies for measuring tyre wear emissions was assessed with the aim of understanding the feasibility of applying these tools in a possible future policy scenario similar to that of exhaust emissions. Input from WP2 (Task 2.3) regarding the relationship of tyres' abrasion rate and particle emissions was assessed with the aim of exploring the feasibility of controlling tyre emissions through their abrasion rate. The technical results obtained in WP2 were also considered to identify whether it is possible to create the foundations for new legislations or the revision of already existent ones.

The impact of the proposed scenarios on public health and well-being of citizens along was examined with a cost-benefit analysis. The Better Regulation toolbox of the European Commission was applied for this purpose. The cost-benefit analysis provided estimations of the costs and benefits to the society as whole but also for various stakeholders. As a final step, clear argumentation for selecting one policy option was provided based on the results of the conducted analysis.

The overall recommendations as well as open issues related to tyre particle emissions were continuously discussed with European Commission and other stakeholders (e.g. in the particle measurement programme (PMP) informal working group) in order to ensure that the objectives of the project remained in line with the objectives of the European Commission. Evidence for the economic and social acceptance of proposed measures were evaluated through stakeholder workshops and public surveys.

4.2. Approach for Task 6.1

Two key elements impacted the outcomes of Deliverable 6.1:

- during the project it was made clear at Leon-T that the vehicle on-board measurement of tyres PM is extremely difficult and uncertain for regulatory purposes;
- the activities at UNECE level defined a regulatory methodology for measurement of tyre abrasion.

In June 2024 an amendment of UNECE Regulation 117 was adopted which added a tyre abrasion measurement. The two methodologies are based on vehicle convoy on-road driving and drum method. In both methodologies the candidate tyres are compared with reference tyres tested at the same time. The reason is that the boundary conditions (e.g. temperature, road) impact the abrasion rate and would make the comparison of different candidate tyres tested under different conditions or different location impossible. A testing campaign is underway in order to assess the market situation in terms of tyre abrasion performance. In the European Union, the Euro 7 emissions standard (EU) 2024/1257 will introduce limits for the abrasion level of tyres starting from 2028 based on UNECE work (**Table 1**).

Table 1. *Euro 7 application dates for tyres of class C1 —typically fitted to passenger cars (PCs), C2 —typically fitted to light-commercial vehicles (LCVs), and C3 —typically for heavy-duty vehicles (HDVs). No specific emission limits have been established yet.*

Legal deadline by tyre class	C1 (PCs)	C2 (LCVs)	C3 (HDVs)
New tyre types from	1 July 2028	1 April 2030	1 April 2032
All tyre types from	1 July 2030	1 April 2032	1 April 2034
Non-compliant in the market until	30 June 2032	31 March 2034	31 March 2036

For these reasons, the analysis focused on tyre abrasion reduction, but PM reductions as a consequence were also evaluated. Furthermore, abrasion values based on the literature were used because the market assessment is not completed yet. Reduction potential was not examined but different Policy cases were examined (10%, 20% and 30%). The 30% is based on the European Union (EU) Zero Pollution Action Plan, which aims to reduce the microplastics release into the environment by 30% by 2030 compared to 2016 levels. **Figure 1** summarises the concept that was followed in this report.

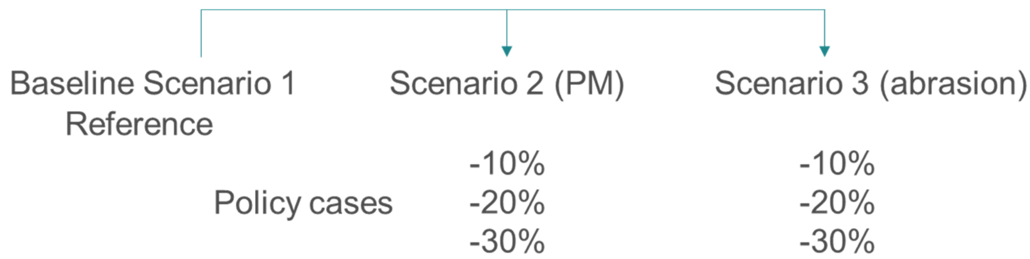

Figure 1: *Scenarios of Task 6.1 and policy cases examined*. A combined scenario (i.e. reduction of abrasion resulting also in PM reduction) will also was evaluated.

5. Methodology

The cost-benefit analyst (CBA) sums the potential rewards expected from an action and then subtracts the total costs associated with taking that action. When different scenarios are assessed, the policy scenario with the highest cost-benefit ratio or absolute difference prevails. The avoidance of pollution from the introduction of Euro 7 tyre abrasion limits, i.e., the emission savings, is expected to create a benefit when expressed in monetised terms. The monetised benefit (in EUR) is calculated by multiplying the emission savings with the external damage costs per unit of pollutant as reported in the Handbook on the external costs of transport (from now on 'Handbook of costs'). However, there is currently no cost estimation for microplastics emission reductions. Furthermore, the tyre abrasion emission factors come with a high uncertainty. In our recent review we collected recent measurements data from passenger cars tyres; however, for vans, buses, and lorries there is still a gap since the testing methodology is not established yet.

To estimate the potential benefits of the application of abrasion rate reductions, two cases are compared: (i) baseline 'Reference' case, considering health burden of microplastics releases from tyres without any abrasion limits and with no additional efforts to improve tyre abrasion performance; (ii) a hypothetical case, where the health burden of microplastics releases from tyres is reduced due to an average tyre abrasion performance improvement of 10%. This case considers administrative costs and research costs related to the improved tyre abrasion performance. In addition, 20% and 30% reduction cases are examined. For each case, $PM_{2.5}$, PM_{10} (scenario 2 according to Task 6.1) and total abrasion (scenario 3 according to Task 6.1) are examined (see also **Figure 1**).

5.1. Time value of money

The Euro 7 limits will be introduced gradually from 2028 until 2034 (**Table 1**). Thus, the analysis focuses on the years 2025-2050. We consider the year 2025 as the reference year. The analysis is also performed for the year 2016 because the EU target of 30% reduction of microplastics releases by 2030 uses 2016 as a baseline. Furthermore, most health cost data in the 'Handbook of costs' refer to 2016. Our analysis follows the 2023 version of the 'Better Regulation Toolbox'.

To convert a value V from one year to another, the following equation is applied:

$$V_{y+Y} = V_y \times (1+f)^Y / (1+r)^Y \qquad \textbf{(Eq. 1)}$$

Where y is the reference year (i.e. 2025 in this report), Y is the time increment in years (e.g., 1 for 2026), f is the inflation rate, and r is the discount rate.

We apply a discount rate of 3% to bring the future values to 2025 and a 1% inflation from 2025 (**Figure 2**). The discount rate value of 3% is given in the 'Better Regulation

Toolbox'. The 1% inflation rate is lower than the pre-Covid-19 value in the EU (on average 2%). The cumulative effect of a fixed 1% inflation rate from 2025 to 2050 is to increase costs by about 30%. With a 3% discount rate, the present (2025) value of 1 EUR in 2050 is less than 50%. The net effect of the modelled discount rate and inflation is that 1 EUR in 2025 will worth 40% less in 2050. For values before year 2025 we use the actual inflation rates.

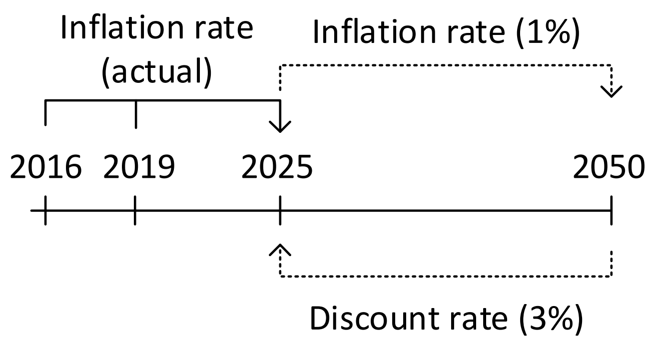

Figure 2. *Application of inflation and discount rates to refer all values to the year 2025*.

5.2. 'Reference' (baseline) scenario 1

The health burden *B* is calculated by multiplying the total mass of the released tyre material (in kg) *TE* and the 'cost burden' or 'damage cost' *D* of the tyre material (expressed as EUR/kg) for pollutant *p* ($PM_{2.5}$, PM_{10}, or abrasion).

$$B_p = TE_p \times D_p \quad \textbf{(Eq. 2)}$$

Table 2 summarises the costs (reference year 2016) as given in the 2019 version of the 'Handbook of costs' for particulate matter (PM) and microplastics. We assumed that the health impact of tyre PM particles is the same as with any other PM. The reason is that recent reviews still consider PM the most representative index for adverse health effects, without identifying one particular component as causing the effects (EPA: Integrated Science Assessment for Particulate Matter, 2019). **Table 2** shows that the values for the UK were similar to the average in the EU28; therefore, we did not apply any correction factor to convert the EU28 to EU27 values. However, we multiplied by 1.3 to convert the 2016 values to 2025 considering an annual inflation of approximately 2% (2016-2020). A correction of annual inflation to 3-9% was applied in the 2021-2023 period (Covid-19 period).

Table 2. *Air pollution average damage cost in EUR/kg for road transport emissions in 2016 (including all effects: health effects, crop loss, biodiversity loss, material damage) for PM in EU28 (first row), our conversions to EU27 and values for microplastics (second row). Estimations for the year 2025 are also given in the third row.*

	$PM_{2.5}$ urban[2]	$PM_{2.5}$ rural	$PM_{2.5}$ motor.[3]	PM_{10}	Microplastics[4]
EU28 (EUR_{2016}/kg)	381 / 123	70	-	22.3	-
UK (EUR_{2016}/kg)	380 / 122	65	-	24.8	
EU27 (EUR_{2025}/kg) [1]	495 / 160	91	29	29.0	7.2

[1] *Adjusted by 1.3 to take into account the conversion of 2016 values to 2025;*
[2] *Numbers refer to metropoles / cities. Metropoles are defined as cities with population >500,000 inhabitants. Urban is calculated assuming 65% of the urban population lives in metropoles and 35% in cities;*
[3] *$PM_{2.5}$ motorway was assumed to be lower than PM2.5 rural, due to lower expected concentrations at citizens (higher dispersion of pollutants). It was set equal to PM_{10}, although the Euro 7 impact assessment study assumed to be equal to $PM_{2.5}$ rural;*
[4] *No data available. We assumed the lowest value from the impact of plastics to the environment (see **Figure 3**) and applied a 1.36 correction to convert 2011 values to 2025 and 0.93 to convert USD to EUR.*

There are no data available for the health or environmental burden of microplastics emissions from tyres. For this reason, the value was estimated based on the data of **Figure 3** that summarises the cost of plastics. In addition the cost of $PM_{2.5}$ and PM_{10} is plotted, which refers to year 2016 as shown in **Table 2**. The environmental costs of plastics are based on a few studies [1–3]. One of the studies focused only on the impact of plastics on the marine environment [1]. The costs include raw material, waste management, and ecosystem service costs. They do not include health impact costs, which are unknown for this newly emerged pollutant. For microplastics, we applied the lowest value (6.3 USD/kg) reported in a plastics study on the environment [3]. This global value was not converted to EU27 due to lack of data on how microplastics emissions are distributed in the EU. However, we applied a 1.23 correction to bring this 2011 value to 2025 based on the inflation rates of the respective years. We also applied an exchange rate of 0.93 USD/EUR. Although not all emitted tyre particles will end up in the eco-system, those that will be captured (e.g. sewage, asphalt) need to be further treated and cleaned. Therefore, there is some cost associated to them as well. The topic will be examined in more detail in Deliverable 6.2 Our approach calculates only the emitted tyre particles due to road-tyre interaction and it does not include tyre particles from e.g., recycled material for crumb rubber and pavements (see e.g., material flow analysis). Furthermore, the estimated costs do not include the environmental pollution from the production of tyres. This could be on the order of 250 g of PM per tyre [4] (note that the tyre wear of one tyre, over its lifetime, was 1,200 g in that study). Thus, even though the calculated value comes with a very high uncertainty, we believe that it is still a conservative (low) value. It should be added that the ‘Handbook of costs’ recommends using the PM_{10} damage cost value for tyres abrasion (microplastics)—a value that is four times higher than the value we assumed.

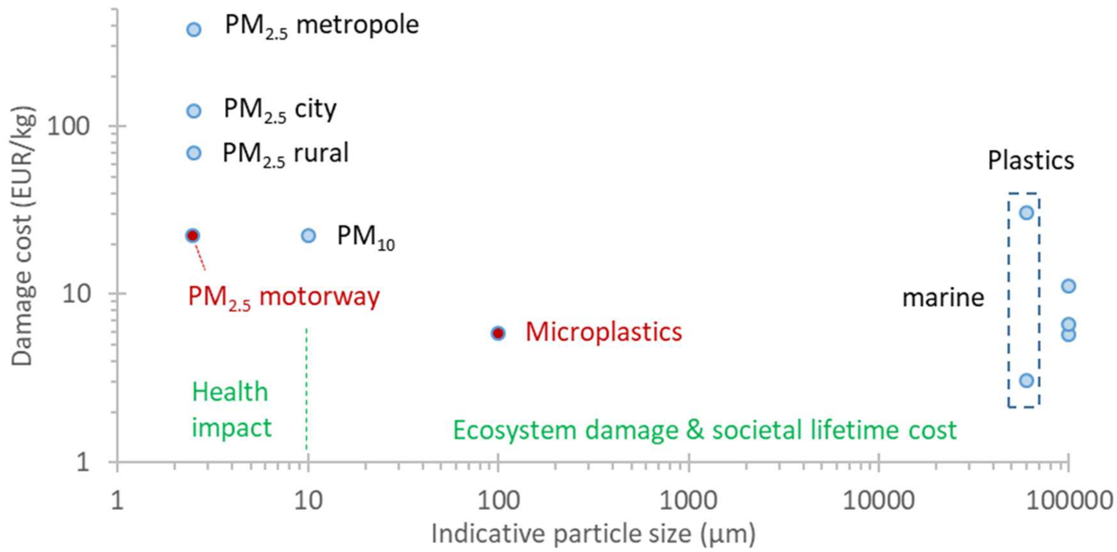

Figure 3. *Reported average damage costs of particulate matter (PM) for the year 2016 and plastics for years 2011-2019, depending on various studies. Values in red are our assumptions. See* **Table 2** *for final used values.*

Equation 3 is typically used in the literature for the calculation of the annual emissions. For example, the COPERT (calculations of emissions from road transport) model uses vehicle population, mileage, speed, and other data such as ambient temperature to calculate emissions and energy consumption for a specific country or region. We followed a similar approach for the annual tyre particles emissions ($TE_{p,j,y}$) in g/km for pollutant p ($PM_{2.5}$, PM_{10}, or abrasion), vehicle category j, and year y.

$$TE_{p,j,y} = N_{j,y} \times M_{j,y} \times EF_{p,j,y} \quad \textbf{(Eq. 3)}$$

Where N is the number of vehicles in operation, M is the annual mileage per vehicle, and EF the tyre emission factor.

We assumed that C1 tyres are fitted to passenger cars (PCs), C2 tyres to vans or so-called light commercial vehicles (LCVs,) and C3 tyres to buses and lorries or so-called heavy-duty vehicles (HDVs). It has to be noted that there is an overlap for some tyres being used also in other vehicle categories. However, this assumption represents the typical vehicle/tyre usage. For this reason, we classified the vehicles into the following categories j: PCs, LCVs, and HDVs. Vehicle stock data or registrations for past years can be found in the literature and in most cases are publicly available. Projections for the future are not publicly available in the literature and depend upon various parameters and assumptions. There are a few studies that have published data (e.g. [5,6]), but these studies do not provide all the information that is necessary for our study and there is some uncertainty due to the Covid-19 period. Other databases and projections (e.g. SIBYL) are covered by commercial licenses. For this reason, we followed a simplified approach. The initial values were taken from European Automobile Manufacturers' Association (ACEA) [7] for years 2016 (baseline) and 2022 (latest year available). We assumed a fleet growth rate of 0.7% per year for the total fleet. This value is lower compared to increases of previous years (on the order of 1.2% until Covid-19).We selected this value based on reported projections from the Euro 7 impact assessment study for exhaust emissions and brake particles [5,8] or older Euro 6 reference scenarios [6]. For electrified vehicles, we assumed a linear growth of 3.2% from 2025 onwards for PCs and LCVs to match recently published projections [8–10]. For the years 2023 and 2024, we assumed slower growth rates of 1.5% for PCs and LCVs due to recent disruptions in the supply chain. For HDVs, we assumed an increasing growth rate of $0.4\%+0.2\%\times Y$, where Y is the incremental year (1 for 2025). The initial percentages of electrified vehicles in 2022 were 5.3% for PCs, 1.1% for LCVs, and 0.5% for HDVs [7].

For PCs, C1 tyres were further subdivided into summer and winter (including all-weather) tyres with 55% and 45% market share, respectively. The values were derived based on the assumption that winter tyres are fitted for half year in most EU countries. However, in Mediterranean countries summer tyres are typically used longer. Based on data from the European Tyre & Rubber Manufacturers Association (ETRMA), in 2021, summer tyres were 55%, winter tyres 30%, and all-season tyres 15% of the replacement tyres sales, thus confirming our assumption.

Table 3 summarises the annual distance travelled per vehicle category based on the literature. The distance was rounded downwards to have a conservative estimate of tyre wear. For PCs we used the population-weighted average distance of ten countries (11,500 km/year) reported by ACEA for 2022 [7]. The value is higher than the average distance during Covid-19 (years 2020 and 2021) but in agreement with the pre-Covid-19 years (e.g. 2018 and 2019) [11]. For LCVs, the most detailed and representative study we found was from the Netherlands in 2017 [12]. This study reported a weighted average of all vans at approximately 18,500 km. For HDVs, we used the average distance per vehicle category given in Regulation (EU) 2019/1242 [13] weighted with its corresponding fleet share [14]. We assumed that the driving distance for HDVs remains constant over the years.

Table 3. *Average annual travelled distance for passenger cars (PCs), light-commercial vehicles (LCVs) and heavy-duty vehicles (HDVs).*

Vehicle category	**Annual distance (km/year)**	**Comment**
PC	11,500 [1]	Based on population weighted average
LCV	20,000 [2]	NL study in 2017 (range 18,600-24,000 km/year)
HDV	100,000 [3]	Range 60,000 – 116,000 km/year

[1] *The exact value was 11,700 km/year; study* [7]

[2] *the exact weighted average was 20,700 km/year; study* [12]

[3] *the exact weighted average was 107,800 km/year. study* [13]

To calculate the health burden of $PM_{2.5}$, the shares of urban, rural, and motorway driving are needed. This is because a higher cost value is assigned to urban areas since these are heavily populated. We assumed the percentages given in **Table 4**, based on the respective regulations applying representative real-world cycles. Furthermore, we assumed that 65% of the urban population lives in metropoles, i.e., cities with population >500,000 inhabitants.

Table 4. *Urban, rural, and motorway shares based on the worldwide light vehicles harmonized test cycle (WLTC) for PCs and LCVs (Regulation (EU) 2017/1151) and the on-road portable emissions measurement systems (PEMS) regulation for heavy-duty trucks (e.g., Regulation (EU) No 582/2011) (the HDV time shares were converted to distance shares).*

Category	Urban	Rural	Motorway	Reference
PC	34%	30%	36%	WLTC
LCV	34%	30%	36%	WLTC
HDV	15%	25%	60%	PEMS

The $EF_{i,j}$ are summarised in **Table 5** and were based on our recent review [15]. A conservative approach was followed (i.e., we took the lowest values). Based on our review, the mean abrasion rate (AR) for conventional PCs with only internal combustion engine (ICE) was 118 mg/km (73 mg/km/t) considering all studies and countries or 100 mg/km (58/mg/km/t) considering only studies in Europe. Excluding studies from UK, to have better EU27 estimation, the average is 108 mg/km (64 mg/km). Estimating an average fleet weight of 1500 kg for PCs with ICE in 2025 we calculate an emission factor of 95.7 mg/km. For LCVs we assumed 2 times higher AR again taking the most conservative approach since in the review it was found to be approximately 2.5 times higher. For HDVs we assumed 8 times higher AR (in the review it was 8-11 times higher). We assumed that the electrified PCs (battery-electric and plug-in hybrid vehicles) (xEVs) are 20% heavier than the internal combustion counterparts, thus resulting in 20% higher AR [52,53]. Based on the review it can be deduced that the tyre microplastics emissions (in mg/km) are proportional to the vehicle weight. For LCVs and HDVs, we assumed that the relative impact of the electrification on the weight is lower (i.e., 15% and 5% respectively instead of 20%) due to the typically higher payload of these two categories. Finally, we assumed that winter tyres have 10% higher emissions, which should include the impact of different temperatures in summer and winter. In our review, the emissions were higher up to 5 times, while another study found 23% difference [16]. Thus, our 10% should be at the conservative side.
After the release of tyre particles, oxidation, mechanical aging, biodegradation and leaching will impact them. In particular biodegradation can reduce the mass of the particles. There is still lack of conclusions regarding the half-life of tyre particles in the environment. For this reason, we did not take into account biodegradation after the release of the tyre particles in this Deliverable. We believe that this effect is covered by

the uncertainty of the emission factors and the uncertainty of the cost of microplastics that we used. The topic will be covered in **Deliverable 6.2**.
Based on our recent review, we assumed that the $PM_{2.5}$ emission factor is 1.6% of the AR and 42% of the PM_{10} factor. This results in the PM_{10} emission factor amounting to 3.8% of the total abrasion rate. This percentage has been reported to be up to 10% in some studies.

Table 5. *Tyre wear emission factors used in this study based on a published review* [15]. *Note that they refer to vehicle level. For example, for a passenger car is the sum of tyre mass loss of all four tyres. The base abrasion rate (AR) to which all emission factors refer to is 95.7 mg/km.*

Tyres		**Cat.**	**Electr.**	**AR**	**PM_{10}**	**$PM_{2.5}$**
C1	sum	PC	ICE	AR	PM_{10}=0.038×AR	PM2.5=0.42× PM_{10}
			xEV	1.20×AR	1.20× PM_{10}	1.20× $PM_{2.5}$
C1	wint	PC	ICE	1.10×AR	1.10× PM_{10}	1.10× $PM_{2.5}$
			xEV	1.10×1.20×AR	1.10×1.20× PM_{10}	1.10×1.20× $PM_{2.5}$
C2	all	LCV	ICE	2.0×AR	2.0× PM_{10}	2.0× $PM_{2.5}$
			xEV	2.0×1.15×AR	2.0×1.15× PM_{10}	2.0×1.15× $PM_{2.5}$
C3	all	HDV	ICE	8.0×AR	8.0× PM_{10}	8.0× $PM_{2.5}$
			xEV	8.0×1.05×AR	8.0×1.05× PM_{10}	8.0×1.05× $PM_{2.5}$

AR=abrasion rate (mg/km); HDV=heavy-duty vehicle; ICE=internal combustion engine; LCV=light commercial vehicle; PC=passenger car; xEV=electrified vehicle (battery and hybrids).

5.3. Scenarios 2 and 3 and Policy cases 10-30%

For the 'Reference' (baseline) scenario we applied the values and assumptions that were described previously, which correspond to no changes of the tyres emission factors over the years. For the second and third scenarios we applied a 10% reduction of all emission factors, and we further examined 20% and 30% reductions. The reason is that the true market values are not known and a market assessment for C1 tyres is currently ongoing. Furthermore, there are no values for the Euro limits yet and no declared intentions. It should also be highlighted, that any limit value does not necessarily apply to the current average value. We also believe that 10% reduction would translate to no changes for the majority of the tyres and thus no need for estimation of research and development costs (see later respective section). The 'high emitting' tyres would have to be improved or they would have to be withdrawn from the market after the application of the relevant regulation. Most companies should be able to easily replace them with existing tyres from their portfolios.

5.3.1. New tyres market penetration

We assumed that the entry into the market of the lower emitting tyres follows the trends summarized in **Figure 4**. These assumptions are based on the Euro 7 dates (fixed by the regulation, see **Table 1**). In general, we assumed that 10% of the tyres enter the market in the 'new types' entry into force date. Note that this date differs depending on the type of tyre (C1, C2, or C3). Based on **Figure 4**, 50% of the tyres shall enter the market at the 'all tyres' date, 90% in the last date allowed for non-compliant tyres in the market, and 100% four years later (see **Table 1** for details). The 90% assumes that 10% of the vehicles will have just been fitted with non-compliant tyres and they will circulate for another four years.

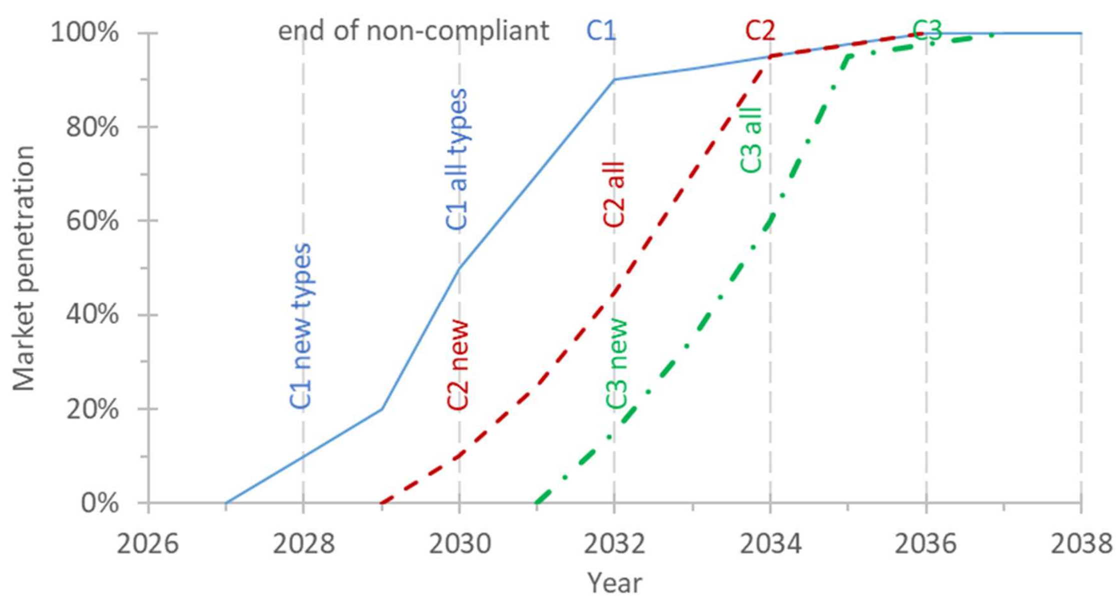

Figure 4. *Market penetration of new 'low emitting' tyres.*

5.3.2. Costs

The costs include the additional (incremental) costs for implementing the regulation:

(i) compliance costs, such as production costs (hardware and manufacturing), research and development (R&D), and initial investment facilities and equipment;

(ii) implementing costs (such as for testing and witnessing), and administrative costs (such as fees to type approval authorities, or for certification).

R&D costs correspond to design, simulation, experimentation, testing, and other activities required to develop and bring the prototype tyres to production level. We calculated the R&D costs assuming one person-year (100,000 EUR) and the need of additional 10 tests per year per tyre type family. We assumed that 33% of the tyre families would need R&D costs for the first four years for each category (C1, C2, C3) for the 10% reduction of emissions case, 66% of the tyre families for the 20% reduction of emissions case, and 100% of the tyre families for the 30% reduction of emissions case. The percentages are the high end of first approximations of shifting theoretical distributions of emissions of tyres and should be refined when the market assessment is completed.

Data on production costs are not widely available. For the 10% case, we believe that there will be no hardware costs as there is no new manufacturing method that needs to be implemented to reduce the abrasion rate of a tyre. We also believe that any change in the formulation of the tyre required to minimize abrasion rate (concentration) will not directly impact the tyre cost. Nevertheless, we estimated the costs by increasing the tyre prices in 2025 by approximately 2%. This resulted in 4 EUR for PCs (i.e. 2 EUR for a 100 EUR tyre, 4 tyres replaced every four years), 3.6 EUR for LCVs (i.e. 2.7 EUR for a 135 EUR tyre, 4 tyres, replaced every three years), and 100 EUR for HDVs (i.e. 10 EUR for a 500 EUR tyre, 20 tyres, replaced every two years). We calculated the costs assuming that 33% of the vehicles (tyres) would be impacted for the 10% reduction case, 66% for the 20% case and 100% for the 30% reduction case. The low (2%) cost increase can be justified by the assumption that there will be no need for different or more costly materials for reduced tyre wear.

Table 6 summarises our assumptions regarding the implementing and the administrative costs. For the first 4 years, we assumed that in total 5,000 tyre families (i.e. 1250 families per year) of C1 tyres need to be tested. To estimate the number of C2 families we multiplied by two the ratio of the LCVs to PCs vehicles (around 12%), resulting in C2 families being 25% of C1 families. The additional factor of two was applied as a safety margin because the exact number of families was not known. Similarly, for C3 families, we multiplied by two the ratio of HDVs to PCs (around 3%), resulting in C3 families being 6% of C1 families. From the fifth year on, we assumed that the renewals – including conformity of production and new type approvals – will be 20% of the total families per tyre category, assuming renewal approximately every 5 years. We assumed that the burden for market surveillance would be 2% of the type approval testing. The testing costs per C1 tyre type (i.e. family head) were based on the high end of offers we received from various companies. We further increased these values by +50% to consider administrative (certification) costs. For C2 and C3 tyres we further increased the costs due to the increased cost of the respective tests (**Table 6**).

Table 6. *Assumptions for implementing and administrative costs*. FC=Families per year.

Vehicle category	Families for the first 4 years	Renewal and new type approvals per year	Market Surveillance	Cost (EUR/tyre type)
PC	1250 (=FC1)	20%×FC1	2%×FC1	15,000
LCV	25%×F (=FC2)	20%×FC2	2%×FC2	20,000
HDV	6%×F (=FC3)	20%×FC3	2%×FC3	50,000

Other costs include:

(i) the potential increased fuel consumption of the new low emitting tyres and

(ii) the health and environmental burden caused by the emissions and CO_2 during the families testing.

Regarding (i), analysis of existing data from the 'general German automobile club' (ADAC) and UTAC actually showed the opposite trend: low abrasion tyres had low fuel consumption. **Figure 5** plots tyre abrasion versus fuel consumption based on data from ADAC and UTAC [17–19]. The scatter is high but the trend is that lower abrasion tyres have also lower rolling resistance and consequently CO_2 emissions. For this reason, we considered that the testing of future 'low' emitting tyres does not increase the CO_2 emissions due to higher rolling resistance. Thus, only the tailpipe CO_2 emissions were considered in the cost (damage to the environment) analysis.

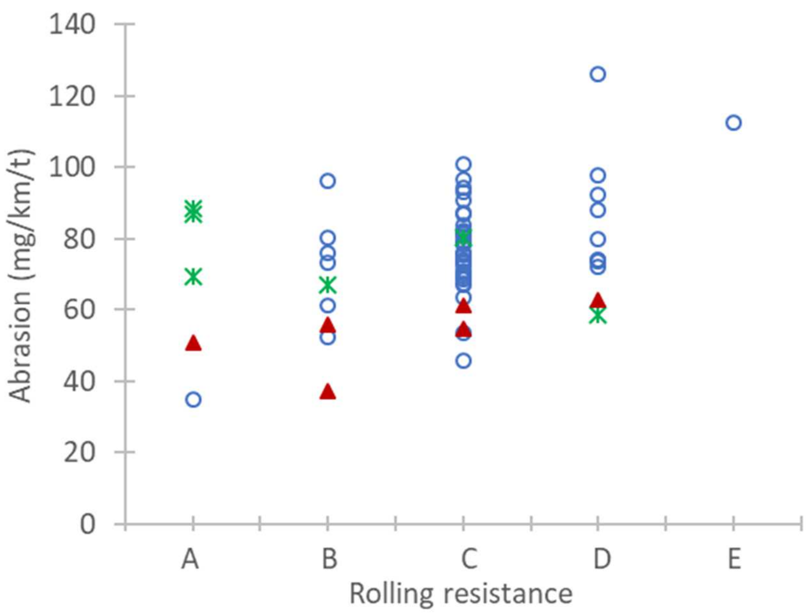

Figure 5. *Tyre wear versus fuel consumption: Circles (ADAC)* [17]*, triangles and asterisks (UTAC)* [18,19].

Regarding (ii) the impact of families on-road testing to the environment we considered a value of 0.29 EUR_{2016}/kg CO_2 (long run) (0.37 EUR_{2025}/kg CO_2) from the 'Handbook of costs' [16]. For PCs we assumed a linear reduction of the CO_2 emissions based on the CO_2 targets as given in Commission's implementing decision (EU) 2023/1623: 93,6 g_{CO2}/km (year 2025), 49,5 g_{CO2}/km (year 2030), and 0 g_{CO2}/km (2035+). Similarly, for LCVs: 153,9 g_{CO2}/km (year 2025) and 90,6 g_{CO2}/km (year 2030). For HDVs we assumed a linear reduction from 780 g_{CO2}/km based on the proposed targets: 45% for 2030, 65% for 2035 and 90% for 2040+ [20]. The rest pollutant emissions (PM_{10} and $PM_{2.5}$ from brakes, tyre abrasion, NO_x, and NH_3) were also assessed assuming representative on-road emission values and pollutants costs from the 'Handbook of costs'. The calculations were carried out for the number of families tested, the mileage of each test (8,000 km for C1 tyres, assumed 10,000 km for C2 and 20,000 km for C3) and the respective tailpipe and tyre pollutant emission factor.

For the final calculation of savings *S* for a pollutant *p* of the policy scenarios we applied the following equation:

$$S_p = \sum_y^{y+n} B_{ref,p} - \sum_y^{y+n} B_{sc,p} - \sum_y^{y+n} C_{sc,p} \quad \textbf{(Eq. 4)}$$

Where *B* is the health burden and *C* are the costs. The difference of the burden between the 'Reference' and 'Policy' scenarios gives the health benefits (savings). Then the costs of the 'Policy' scenario implementation have to be subtracted to calculate the net benefits (savings).

6. Results

6.1. Fleet projections

Figure 6 plots the fleet stock projection until 2050. It is projected that the EU fleet will count 352 million vehicles in 2050. 307 million vehicles will be PCs and 37 million vehicles will be LCVs.

Based on available projections, we expect that in 2030 electrified PCs will consist approximately 27.5% of the fleet. This percentage will increase to 59.5% in 2040 and to 91.5% in 2050. Starting with a 1,535 kg average PCs fleet weight in 2025 and assuming on average 20% heavier electrified compared to conventional vehicles, we get an approximate 1,735 kg average fleet weight in 2050 due to the increasing share of electrified vehicles (16% heavier).

Regarding LCVs, we expect a 23.3% share of electrified LCVs in 2030, 55.3% in 2040, and 87.3% in 2050. Regarding HDVs, we expect 8% electrified HDVs in 2030, 35% in 2040, and 82% in 2050.

Based on the above assumptions the total road transport activity exceeds 5,000 billion vehicle km in 2050. Two thirds of them are driven by passenger cars.

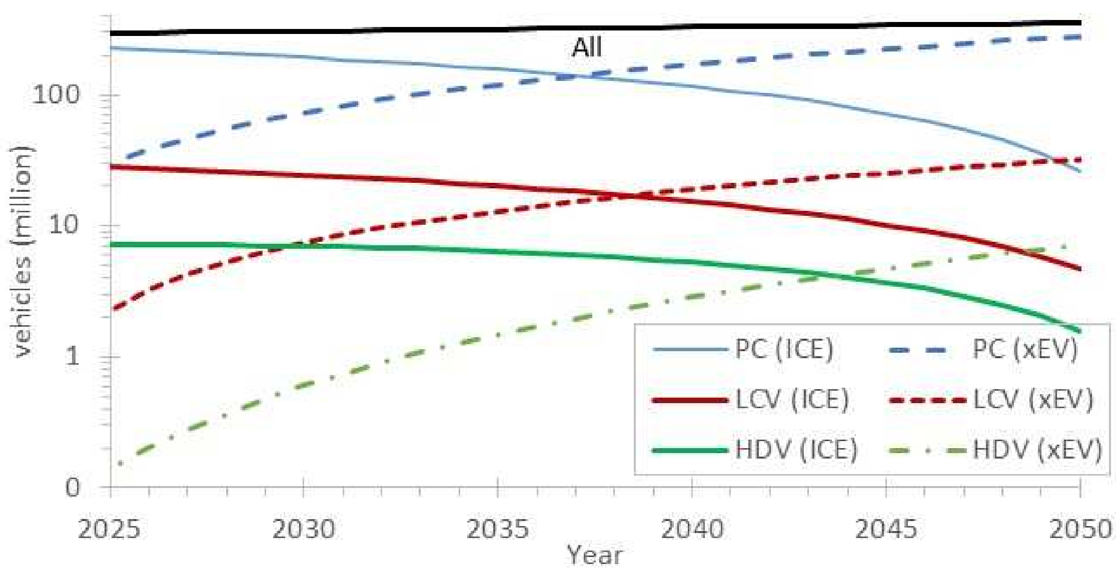

Figure 6. *Projection of fleet stock of passenger cars (PCs), light-commercial vehicles (LCVs), and heavy-duty vehicles (HDVs), with further sub-division in conventional vehicles with internal combustion engine only (ICE) or electrified vehicles (xEV).*

Figure 7 plots the annually emitted tyre wear mass. It can be seen that emitted tyre wear mass increases from 985 kt in 2025 to 1270 kt in 2050. For completeness, the 2016 reference value was approximately 867 kt assuming the same emission factors. The increase of the reference abrasion mass over time is due to the increase population of the fleet (0.7% per year) and the increase of the average fleet weight due to electrification (around 20%).The aforementioned value lies between the estimates from other pre-Covid studies 500 kt [21,22] and 1,327 kt [23]. We estimated that the contribution from PCs is 32% (±1%) and from HDVs 56% (±1%). Despite the PCs fleet is 35 times higher compared to HDVs, their lower contribution is due to their 8 times higher emission factors and 8.5 times higher annual mileage of HDVs. In general, in Nordic countries PCs contribute 2/3 of the tyre wear, while low contribution is reported for the United States, India, and South Korea [24]. For Nordic countries, this also relates to the use of studded tyres that result in much higher wear. However, it remains important to determine accurately the HDVs emission factors in the future.

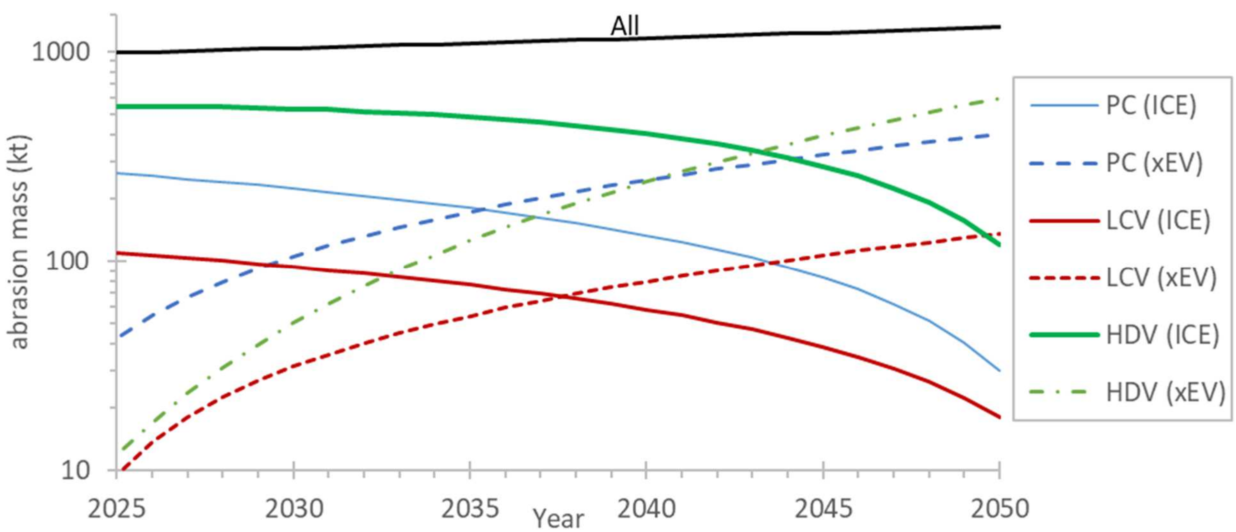

Figure 7. *Mass of emitted tyre wear particles. The contribution of passenger cars (PCs), light-commercial vehicles (LCVs), and heavy-duty vehicles, with further sub-division in conventional vehicles with internal combustion engine only (ICE) or electrified vehicles (xEV) is also plotted.*

6.2. Savings

Figure 8 compares the -10% case for scenario 3 (abrasion) with the 'Reference' one. Due to the gradual introduction of the limits (**Table 1**) followed by the gradual introduction of low emitting tyres in the market, the 10% reduction per year is foreseen to be achieved around 2035. Following that year, the 'Reference' and the 'Policy scenario' lines appear to come with a constant 10% difference. Thus, the 10% reduction of the mean emission factors results in total 7% reduction of the tyre wear mass emitted to the environment in 2050. In terms of mass, in total, approximately 2,115 kt of less tyre wear mass is emitted to the environment following the 10% case. This corresponds to approximately 10,845 EUR savings from reduced tyre abrasion mass.

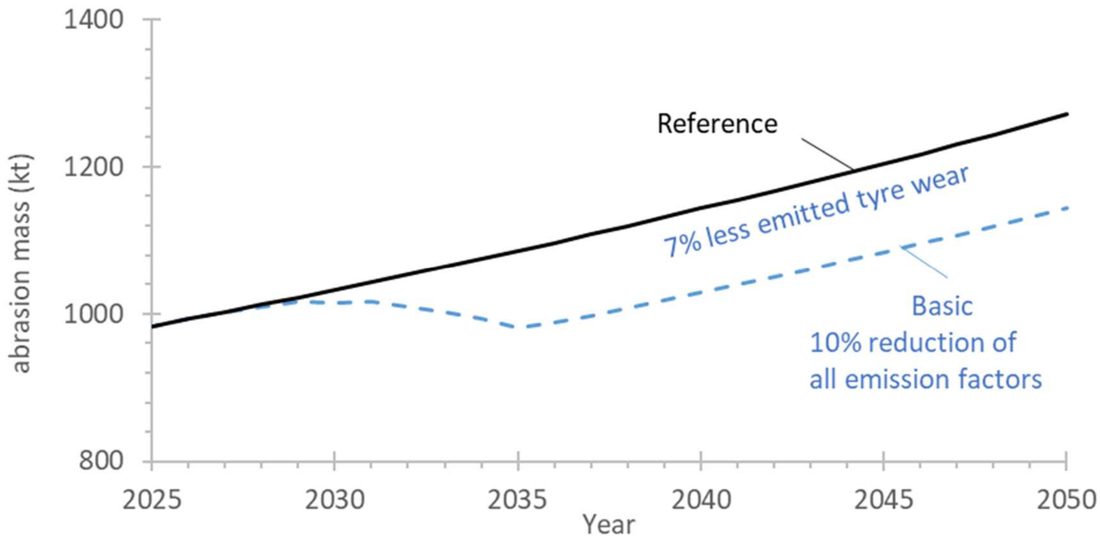

Figure 8. *Emitted abrasion mass at the 'reference' and 'basic' scenario 3*. The increase of the reference abrasion mass over time is due to the increase population of the fleet and the increase of the average fleet weight due to electrification.

Table 7 summarises the results of the 'Policy' case (10% reduction of the emission factors) for abrasion (Scenario 3), PM_{10} (Scenario 2), and $PM_{2.5}$ (Scenario 2). Reduction of 10% of the emission factors will reduce 2,115 tyre mass, 82 kt PM_{10} and 34 kt $PM_{2.5}$ with corresponding savings of 10,845 million EUR, 1,688 million EUR, 3,412 million EUR, respectively.

Table 7. *Calculated benefits of the 'Policy' scenario (-10%) compared to the 'Reference' scenario.*

	Abrasion	**PM_{10}**	**$PM_{2.5}$**
Policy case -10%	**Scenario 3**	**Scenario 2**	**Scenario 2**
Assumed contribution to total mass	100%	3.8%	1.6%
Less mass (kt)	2,115	82	34
Cost savings (million EUR)	10,845	1,688	3,412

As it was mentioned at the introduction regulating PM is difficult as there is no methodology and no robust emission factors. Euro 7 regulates total abrasion. Assuming that reduction of the total wear will reduce proportionally PM, then the total (discounted) cost savings can be calculated by summing the abrasion and PM cost savings, excluding the overlapping areas: 14,825 million EUR (and not the sum of the three that would be 15,946EUR).

Figure 9 plots how the cost of tyre wear particles can be calculated. We assumed a mass size distribution where $PM_{2.5}$ is 1.6% of the total mass and PM_{10} 3.8%. To calculate the total tyre wear cost we added the 100% $PM_{2.5}$ cost with the incremental PM_{10} cost (2.2% from 3.8% of total mass, i.e. 58% of the PM_{10} cost), and the 96.2% (100% minus 3.8%) of the abrasion cost.

The burden *B* can be calculated by summing the abrasion and PM cost savings, excluding the overlapping size range considering the percentages *P* of each pollutant (see **Figure 9**):

$$B = B_{PM2.5}\times 100\% + B_{PM10}\times(P_{PM10}-P_{PM2.5}) / P_{PM10} + B_{abrasion}\times(P_{abrasion}-P_{PM10}) \quad \text{(Eq. 5a)}$$

$$B = 3{,}412\times 100\% + 1{,}688\times 58\% + 10{,}845\times 96.2\% = 14{,}825 \text{ million EUR} \quad \text{(Eq. 5b)}$$

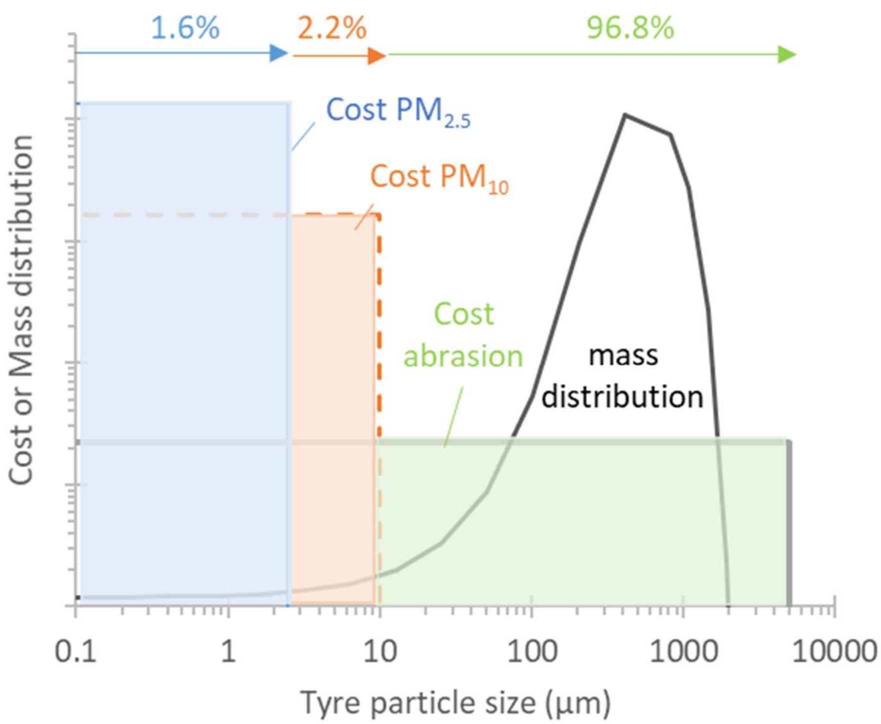

Figure 9. *Calculation of tyre wear costs*. The size distribution is shown for illustrative reasons only and was not used for any calculation.

6.3. Costs

The costs due to CO_2 pollution from families testing (type approval and market surveillance) is around 4.4 million EUR. The costs due to tyre abrasion, PM, NO_x, and NH_3 pollution from testing is around 0.5 million EUR. The testing and administrative costs are calculated 300 million EUR.
In case additional R&D costs are necessary, then these would be around 558 million EUR for the -10% 'Policy' case. It is unlikely that any production costs would be necessary even with high reduction of the abrasion rate limits. In case the production costs in-crease, as described in the Methods section, the cost for the -10% 'Policy' case would be 6,593 million EUR averaging around 285 million EUR per year (over 23 years).
Figure 10 plots the costs and benefits over the years until 2050. The net value (black dotted line) is negative during the first years but becomes positive in 2029 assuming no

production costs. The net value line becomes anyway positive in 2032 with production costs (black continuous line). The net benefit is very high; thus, it is unlikely that any other scenario or different assumptions would lead to different conclusions.

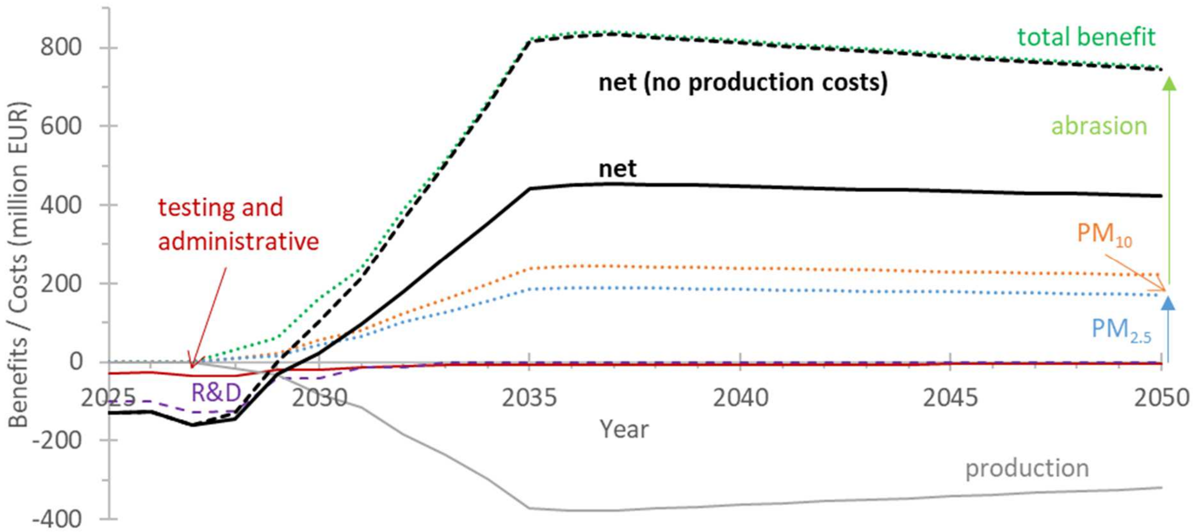

Figure 10. *Costs and benefits over the years for the 'Basic' scenario. The environmental costs of the testing are not plotted as they are negligible (<1% of the test and administrative costs).*

The analysis showed a clear positive impact of reducing tyre wear. Even for a relatively small decrease of the emission factors (10%) there is a net benefit of 14,825 million EUR (or 7,373 million EUR assuming one third of the tyres will increase their price due to production costs of 6,593 million EUR) (**Table 8**). To put the results into perspective, the introduction of PCs and LCVs brakes PM_{10} limits will save 280 kt by 2050. This is expected to bring a health benefit of 9,900 million EUR against a cost of 6,600 million EUR. The overall net benefit of introducing PCs and LCVs brakes PM10 limits is expected to be around 3,300 million EUR [5]. It has to be highlighted though that the positive effects of the tyre abrasion regulation will be manifested after some years as is the case in all similar regulations. More specifically, only after 2035 the full benefit of the new tyre abrasion regulation is at maximum.

Table 8 summarises the calculated net benefits for the 20% and 30% emission factors reductions, in addition to the 10% 'Policy' case that was presented so far in detail. The benefits are almost proportional (e.g., compare 'Policy' 10% vs '20% reduction' scenarios).

Table 8. *Calculated benefits of the 'Policy' cases compared to the 'Reference' scenario in million EUR. $PM_{2.5}$, PM_{10}, Abrasion give the savings independently*.

Pollutant	**$PM_{2.5}$**	**PM_{10}**	**Abrasion**
Policy case	**Scenario 2**	**Scenario 2**	**Scenario 3**
Policy 10% vs. Reference (**Table 7**)	3,412	1,688	10,845
EFs reduction 20% instead of 10% [1]	6,825	3,377	21,691
EFs reduction 30% instead of 10% [2]	10,237	5,065	32,536

[1] for this scenario we assumed that 66% of the tyres will be impacted (not only 33%);
[2] for this scenario we assumed that 100% of the tyres will be impacted (not only 33%).

Table 9 extends the information considering the costs of different cases (net savings) for Scenario 3 (only abrasion limits) but considering that PM will be decreased proportionally to the abrasion.

Table 9. *Calculated benefits of the 'Policy' cases (Scenario 3) compared to the 'Reference' scenario in million EUR. Column Savings gives the combined benefit (**Eq. 5**). Net is the savings minus administrative, R&D, and production costs, while Net (no prod.) does not take into account production costs.*

Policy case	**Savings**	**Net**	**Net (no prod.)**
Policy 10% vs. Reference (**Table 7**)	14,825	7,373	13,966
Policy 20% vs. Reference [1]	29,650	15,047	28,233
Policy 30% vs. Reference [2]	44,475	22,503	42,482

[1] for this scenario we assumed that 66% of the tyres will be impacted (not only 33%);
[2] for this scenario we assumed that 100% of the tyres will be impacted (not only 33%).

7. Summary

In this study we conducted a cost-benefit analysis to evaluate the costs and savings of PM (Scenario 2) or abrasion rate (Scenario 3) reductions compared to the baseline reference Scenario 1. One ‘Policy’ case assumed a basic 10% reduction of all emission factors following the gradual Euro 7 implementing dates for C1, C2 and C3 tyres. Variations of this basic case to test other hypotheses (with 20% and 30% reduction of emissions factors) were also analysed.

The basic 10% scenario resulted in 7% less mass from abrasion until 2050 (2,115 kt less mass), with cost savings of 11,000 million EUR from reduced tyre abrasion; 1,700 million EUR from less PM_{10} and 3,400 million EUR from less $PM_{2.5}$. The combined benefit was 15,000 million EUR (excluding overlapping size regions). Taking into account testing and administrative, research and development costs, the net benefit was still a significant 14,000 million EUR. Assuming that the high emitting tyres would increase their price due to production costs (2% per tyre), the net benefit for the 2025-2050 period would be halved (7,300 million EUR). The positive impact will start to be visible between 2029 to 2032 (depending on the assumed costs) and will reach the maximum per year in 2035.

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