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Demandeur ***Applicant***	**EUROPEAN AUTOMOBILLE MANUFACTURERS ASSOCIATION – ACEA** 85 AVENUE DES NERVIENS 1040 BRUXELLES BELGIQUE		
Objet ***Subject***	Etude sur l'Abrasion des Pneumatiques – Livrable WP1 -Etude Bibliographique *Study on Tyre Abrasion – Work Package WP1 – Literature Review*		
Service / Lieu des essais ***Unit / Test site***	UTAC France Autodrome de Linas Montlhéry BP 20212 91311 Montlhéry Cedex - France		
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Technicien(s) ***Technician(s)***			
Conclusion ***Conclusion***	A literature review was carried out on the following tyre wear / abrasion aspects: - Driving behaviour influence - Vehicle design influence - Tyre performances interdependency - Tyre wear / abrasion testing - Tyre & Road Wear Particles emissions ☐ **CONFORME**/*COMPLY* ☐ **NON-CONFORME**/*NOT-COMPLY* ☒ **NON-APPLICAPLE**/*NOT-APPLICABLE*		
Avertissement ***Warning***	Ce rapport est un constat d'essai et ne constitue pas un rapport d'homologation *This report is a test report and does not constitute an approval report.*		

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Table of Contents

1. LITERATURE REVIEW OBJECTIVE

As part of the study on tyre wear and abrasion influencing factors, the scope of the literature review was the studies published worldwide, in English, on tyre abrasion and mileage for C1, C2 and C3 tyres (Summer and 3PMSF). The following aspects were especially considered:

- Driving behaviour influence on tyre wear / abrasion,
- Vehicle design influence on tyre wear / abrasion,
- Tyre performances interdependency,
- Tyre wear / abrasion testing,
- Tyre & Road Wear Particles (TRWP) emissions.

The review included, but was not limited to, the relevant studies presented in the various UNECE Informal Working Groups (IWG) and Task Forces (TF), including the previous UTAC tyre performance studies for ACEA and ETRTO.

2. TYRE WEAR / ABRASION OVERVIEW

To better understand the different aspects of the tyre wear and abrasion discussed in the literature review, first the tyre wear basic mechanics are presented along with the main tyre wear influencing parameters.

2.1 TYRE WEAR / ABRASION BASIC MECHANICS

A tyre main function is to carry the vehicle load and to contribute to the vehicle handling by transferring the forces between the vehicle and the road during the vehicle acceleration / braking and cornering. While doing so, frictional work is generated in each tyre tread element in the tyre contact patch at the interface between the tyre and the road. This results in the tyre tread wear or abrasion.
Tyre wear can be considered proportional to the frictional energy as per the following equation [6]:

$$R_w = A \times F_E$$

Where,

R_w is the rate of wear, the amount of rubber lost from a unit of tread surface per tyre revolution,

A is the abradability, the amount of rubber lost in a tyre revolution per unit area per unit frictional work under specified interface conditions,

F_E is the frictional work or energy per unit area, per revolution, for a typical tread element.

The abradability and the frictional energy factors are shown in the Figure 1 overleaf:

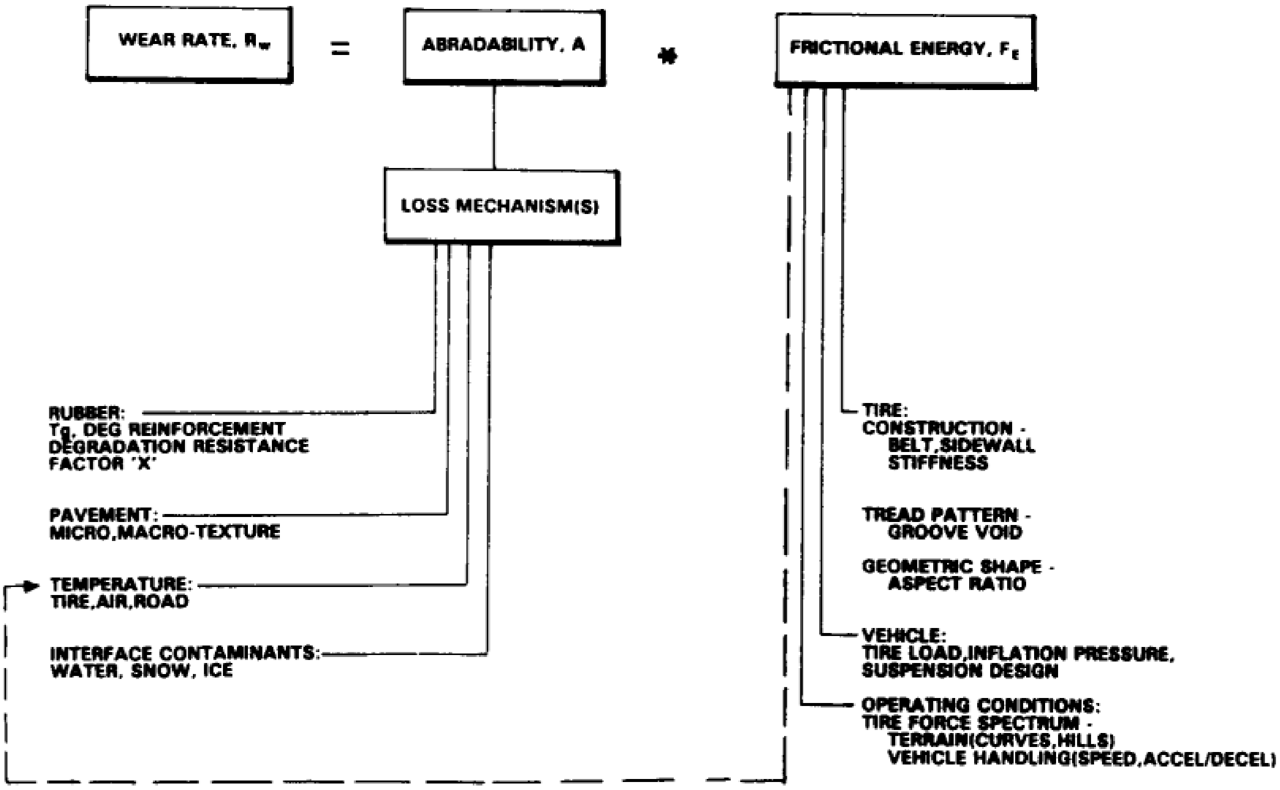

Figure 1: Tyre Wear Equation [6]

Tyre abrasion is a physical as well as a chemical process where oxidation and thermal decomposition play important roles [5] [6]. Different wear mechanisms can be considered [4]:

- Adhesive wear: removal of material caused by high transient adhesion ('welding'),
- Abrasive wear: caused by cutting-rupture action of sharp angular asperities on the sliding counterface or as third bodies (particles),
- Erosive wear: cutting-rupture action of particles in a liquid (fluid) stream,
- Corrosive wear: from direct chemical surface attack,
- Fatigue wear: caused by rapid or gradual material property changes that give rise to cracks and with their growth, a loss of material.

2.2 TYRE WEAR / ABRASION INFLUENCING PARAMETERS

Tyre wear depends on the parameters that modify the forces applied to the tyre or change of the rubber / ground interface. The factors affecting tyre wear are shown in the Figure 2 overleaf:

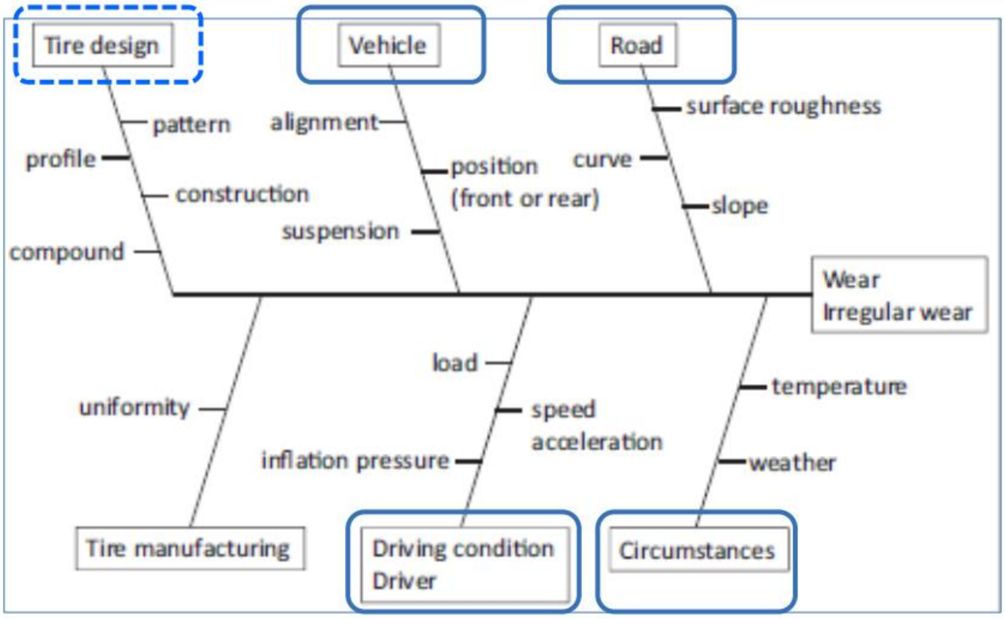

Figure 2: Factors affecting Tyre Wear [2]

The relative weights of the different influencing factors on tyre abrasion rate are shown in Figure 3 below:

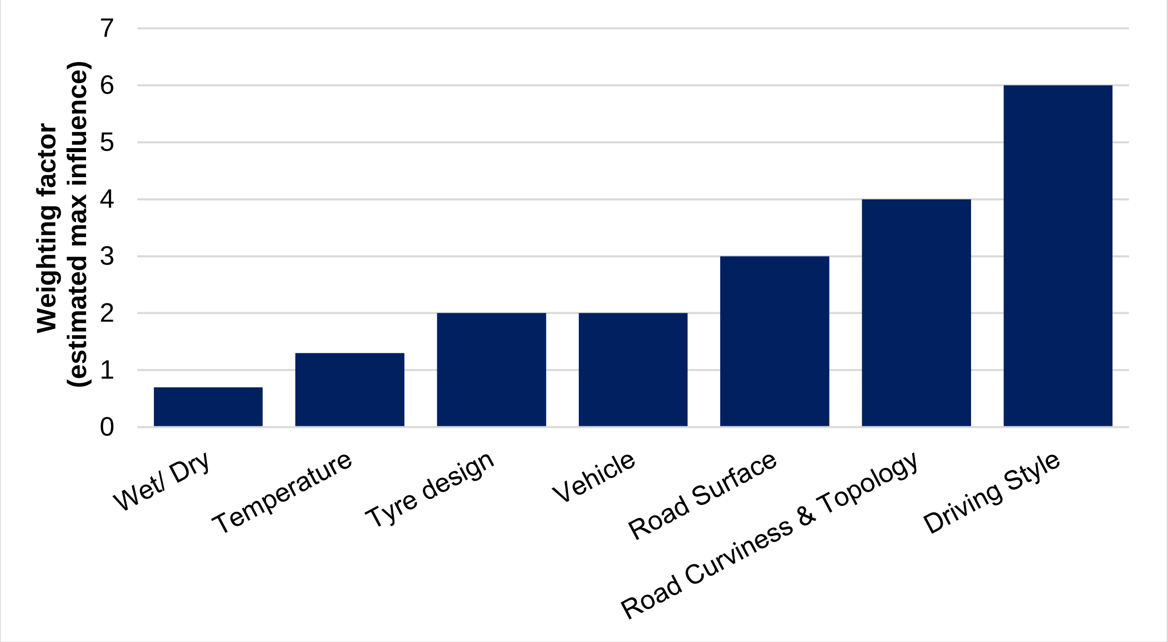

Figure 3: Influencing Factors on Tyre Abrasion Rate & Factors Weight [1]

The driving style and the road are the most influencing factors followed by the vehicle and tyre design [3] [5].

2.3 REFERENCES

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[6] Veith, A. G., A Review of Important Factors Affecting Treadwear. Rubber Chemistry and Technology 1 July 1992; 65 (3): 601–659

3. DRIVING BEHAVIOUR INFLUENCE ON TYRE WEAR / ABRASION

3.1 LONGITUDINAL AND LATERAL ACCELERATION

Tyre force is the most important frictional energy factors (see Figure 1). The most important forces are due to the vehicle inertia when there is a change in the velocity magnitude or direction [6]. Lateral forces have been shown to be more important and more frequent than longitudinal forces in normal vehicle use.
The relation between tyre wear rate and lateral force can be described by the following equation [7]:

$$R_w = KF^n$$

Where,
R_w is the wear rate in mm/10000km,
F is the tyre force in N,
K is a constant,
n is an exponent usually between 2 and 4 depending on the pavement abrasiveness (2 for many pavements).

If the lateral force, F, is given by the following equation:

$$F = W \times \frac{V^2}{R} \times G = W \times g$$

Where,
W is the vehicle weight in N,
V is the velocity in m/s,
R is the curve radius in m,
G is the acceleration constant 9.8m/s^2,
g is the acceleration expressed in dimensionless units relative to G, it is also the ratio of the tangential (lateral or longitudinal) force to the normal force for a tyre where the normal force is the tyre load.

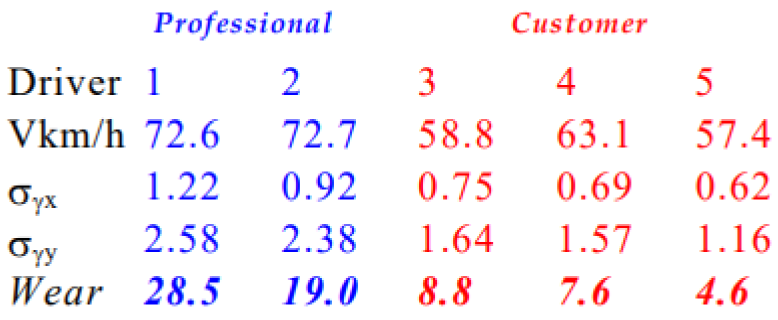
Then, considering n = 2, the tyre wear rate can be expressed as follow:

$$R_w = K \times W^2 \times \frac{V^4}{R^2} \times G^2 = K \times W^2 \times g^2$$

The wear rate depends on:

- The square of the vehicle weight with curve radius and the vehicle constant,
- The vehicle velocity to the power of 4 with the curve radius and the vehicle weight constant,
- The square of the inverse curve radius with the vehicle velocity and weight constant.

This means that the effect of the driving style can be quantified by measuring the tyre wear on the same vehicle driven by different drivers over the same course as shown in Figure 4 overleaf:



	Professional		Customer		
Driver	1	2	3	4	5
Vkm/h	72.6	72.7	58.8	63.1	57.4
$\sigma_{\gamma x}$	1.22	0.92	0.75	0.69	0.62
$\sigma_{\gamma y}$	2.58	2.38	1.64	1.57	1.16
Wear	***28.5***	***19.0***	***8.8***	***7.6***	***4.6***

Figure 4: Driver Influence on Tyre Wear [3]

3.2 VEHICLE SPEED

Higher speeds are shown to be associated with increased tyre wear. According to one study, tyre wear can vary exponentially with truck speed (20 to 120kph). Some other studies found linear relationship between tyre wear and vehicle speed (36 to 144kph) [4].
However, when considering the amount of wear observed for different driving conditions and their associated level of speed, as listed below, there does not seem to be any direct correlation [1]:

- High wear observed during urban driving with low speed but frequent accelerations (longitudinal and lateral),
- Medium wear observed during rural driving with intermediate speed and occasional accelerations (longitudinal & lateral),
- Low wear during motorway driving with high speed, rare accelerations (longitudinal & lateral) and air drag.

This confirms that the tyre wear depends on speed through its correlation with acceleration, ie: the rate of change of the vehicle speed and direction of motion.

Promoting eco-driving and traffic flow management, ie maintaining lower and constant speeds, has been identified as an effective solution to reduce the tyre wear emissions with a high mitigation potential and medium implementation efforts / costs but with a high societal impact [5]. It is considered that self-driving cars could be programmed to reduce wear and tear [2].

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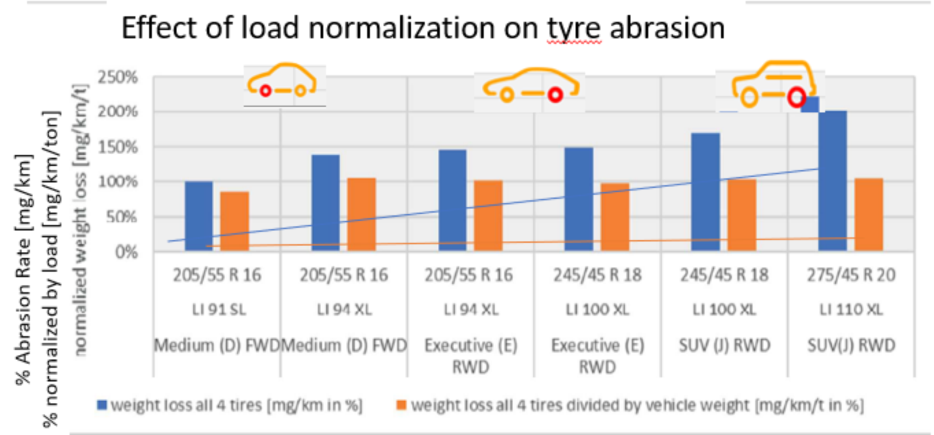
4. VEHICLE DESIGN INFLUENCE ON TYRE WEAR / ABRASION

4.1 VEHICLE WEIGHT AND GEOMETRY

Several studies have shown the link between increased tyre wear and increased weight through testing and simulation. Higher contact pressure between the tyre and the road due to increasing vertical load leads to higher slip forces and then more severe wear [9]. The wear on an axle is quasi-proportional to the load imposed [5] [6] [14].

A dedicated Design of Experiment and the results showed that the total tyre abrasion rate increased with the vehicle total mass and that a linear dependence is a good approximation as per the Figure 5 below:



VDI, Reifen - Fahrwerk – Fahrbahn. 22.05.2022, Aachen; Buschmeier/Oelze. „Einfluss von Reifengröße und Fahrzeuggewicht auf Abriebrate und Laufleistung von PKW-Reifen"

Figure 5: Tyre Abrasion Rate Evolution with Vehicle Total Mass [3]

The tyre abrasion rate per vehicle normalised by the vehicle load is constant.

With regards to tyre wear particle emissions, rate of tyre wear emissions per vehicle-km per kg of vehicle weight have been calculated [9]:

- PM10: 0.0041-0.0046 mg/kg,
- PM2.5: 0.0029-0.0032 mg/kg.

With regards to the electrification impact on vehicle weight, the assumption is that the increased EV weight due to the battery pack leads to increased tyre wear and to possibly higher tyre wear particle emissions. The difference in weight between an EV and the equivalent ICEV is estimated to be currently around + 20-25%. Assuming a linear relationship between weight and tyre wear emissions, the expectation is that the tyre wear emissions are about 20-25% higher with an EV [1] [5] [10] [14].

Reductions in vehicle weight has been identified as an effective solution to reduce the tyre wear emissions with a medium to high mitigation potential and medium implementation efforts / costs but with a medium to high societal impact [1] [5] [11].

With regards to vehicle geometry, it influences the tyre wear through the air resistance it creates and through the load distribution between the front and rear axle [12].

4.2 VEHICLE ARCHITECTURE

4.2.1 FRONT WHEEL DRIVE (FWD) VS REAR WHEEL DRIVE (RWD)

On a vehicle, the tyres that experience the higher tyre forces wear at a faster rate. This corresponds to the front tyre on a Front Wheel Drive (FWD) vehicle since they are more heavily loaded, must propel the vehicle and generate a greater part of the cornering force compared to the rear tyres. On a Rear Wheel Drive, the wear rate is more balanced between the front and rear tyres since the rear tyres are less heavily loaded and generate less cornering force even though they propel the vehicle [13].

4.2.2 INTERNAL COMBUSTION ENGINE (ICE) VS ELECTRIC VEHICLE

From a vehicle architecture point of view, Electric Vehicles are expected to have a longer wheelbase and a more centered mass compared to ICE vehicles, as shown on the Figure 6 below:

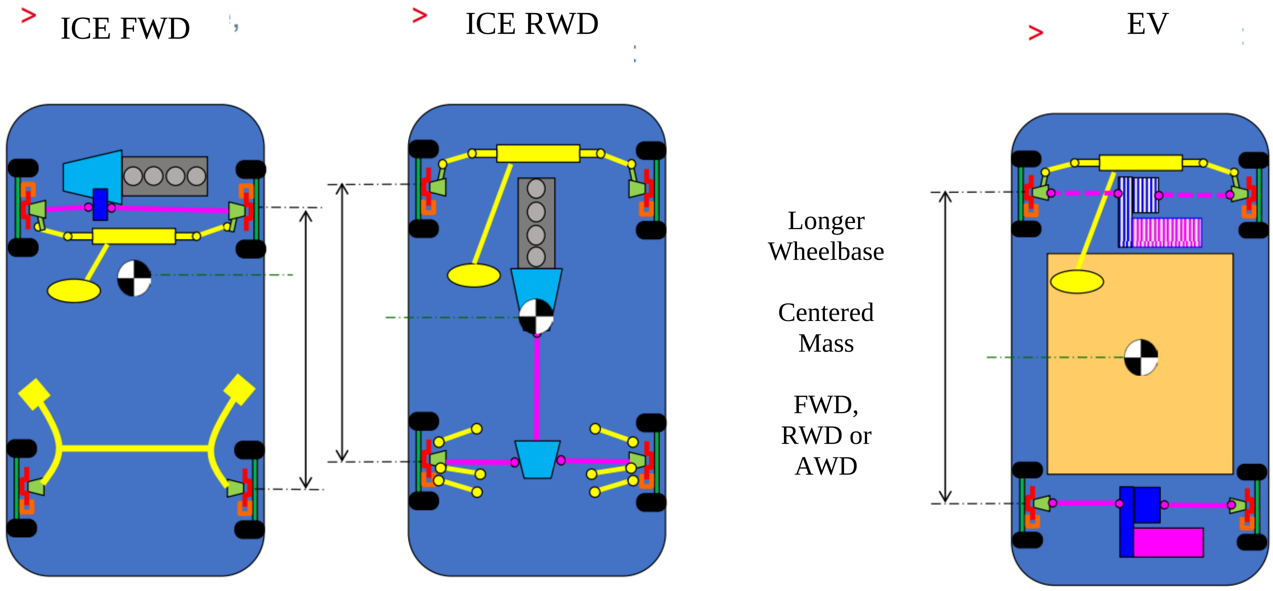


Figure 6: ICE vs EV Vehicle Architecture [2]

These characteristics, along with the expected 20-25% weight increase due to the battery pack mentioned previously, mean that the load increases more on the rear axle.

With regards to engine / braking torque distribution, Electric Vehicles higher level of instantaneous torque and regenerative braking system need to be considered [11].

On an ICE vehicle, the driven axle, whether it is the Front or the Rear one, is more loaded considering the load transfer while the braking is split between both axles with the front axle being more solicited. On an EV, the driven axle is not always the most loaded (for instance if FWD Commercial Vehicles are considered) and the regenerative braking only applies on the driven axle. This means that, if a FWD EV is considered, more adherence will be needed for the same acceleration and the front tyres will be more solicited during all use phases. However, if a RWD EV is considered, more adherence will be needed for the same deceleration during regenerative braking and the rear tyres will be more solicited during regenerative braking.

As a consequence, on an EV RWD, tyre wear can be increased by at least 20% compared to an equivalent ICE vehicle and, on an EV FWD, tyre wear can be twice as much as on the equivalent ICE vehicle [2].

With regards to the electrification impact on the driving behaviour, especially related to the instantaneous torque availability, a study was made to compare the usage severity (average accelerations) between an Electric Vehicle (EV) and an Internal Combustion Engine Vehicle (ICEV). The results showed that after an initial stronger usage severity from the EV drivers compared to the ICE driver, the differences disappeared after a few months [8].

4.3 SUSPENSION GEOMETRY

The type of suspension, which determines the wheel alignment, i.e.: the amount of camber angle experienced by the tyre during cornering, as well as the static toe-in and camber angle settings, which influence the vehicle dynamic handling, have an impact on the tyre wear, both in terms of amount of wear and worn profile [6] [12] [13].
Tyre mass loss rate increases with increased static toe-in and camber angles as shown in Figure 7 below:

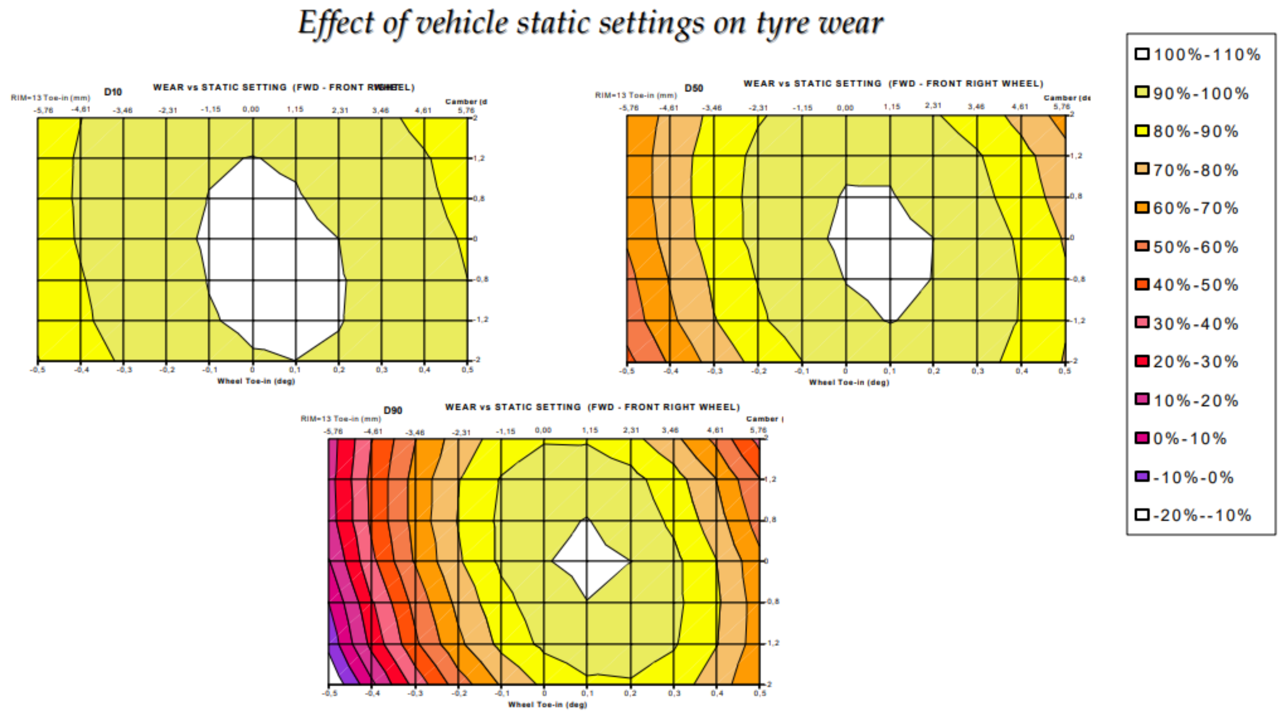


Figure 7: Effect of vehicle suspension static settings on tyre wear [6]

To ensure a regular tyre wear profile, static toe-in and camber angle settings need to be specified together. Toe-in combined with negative camber will lead to tyre inner shoulder wear while toe out combined with positive camber angle will lead to tyre outer shoulder wear.
Since they are less solicited in terms of load and cornering forces, rear tyres on FWD vehicles frequently show tendencies towards irregular wear due to suspension static settings. [13]

During vehicle use, incorrect wheel alignment may increase tyre wear rates by up to 10%. Wheel alignment optimisation has been identified as an effective solution to reduce the tyre wear emissions with a medium mitigation potential and low implementation efforts / costs and with a medium societal impact. [11]

4.4 TYRE INFLATION PRESSURE

The way the tyre inflation pressure influences the tyre wear is complex. It acts on the shape of the contact patch and on the tyre stiffnesses. For instance, a lower inflation pressure reduces the cornering power (force per degree of slip angle), increases the tyre deflection and increases the total footprint area. For a specific tyre, the net effect will depend partly on how the inflation pressure influences the distribution of crown to shoulder wear. [13]

Under-inflation and over-inflation lead to uneven tyre wear profile. Maintaining optimal tyre inflation pressure has been identified as an effective solution to reduce tyre wear emissions with a medium to high mitigation potential and low implementation efforts / costs and a medium societal impact. [11]

4.5 HEAVY DUTY VEHICLES (HDVs) TYRE WEAR

HDV tyre wear varies from low to severe depending on the type of vehicles (trucks, buses, coaches) and the use cases considered. For instance, trucks can be used for long haul or regional or urban delivery. The specific case of long haul trucks is detailed here. Long haul trucks operate mainly on motorways, where acceleration levels are low, and so display the lowest tread wear with typical wear rates as follow [7]:

- Front axle: 15,000 - 30,000 km/mm tread depth loss,
- Rear axle: 10,000 – 15,000 km/mm tread depth loss.

Long haul trucks are usually used at their maximum transport capacity which means truck tyres always work at their maximum load. Figure 8 below shows the load distribution on the axles of a typical 40-ton truck-trailer combination.

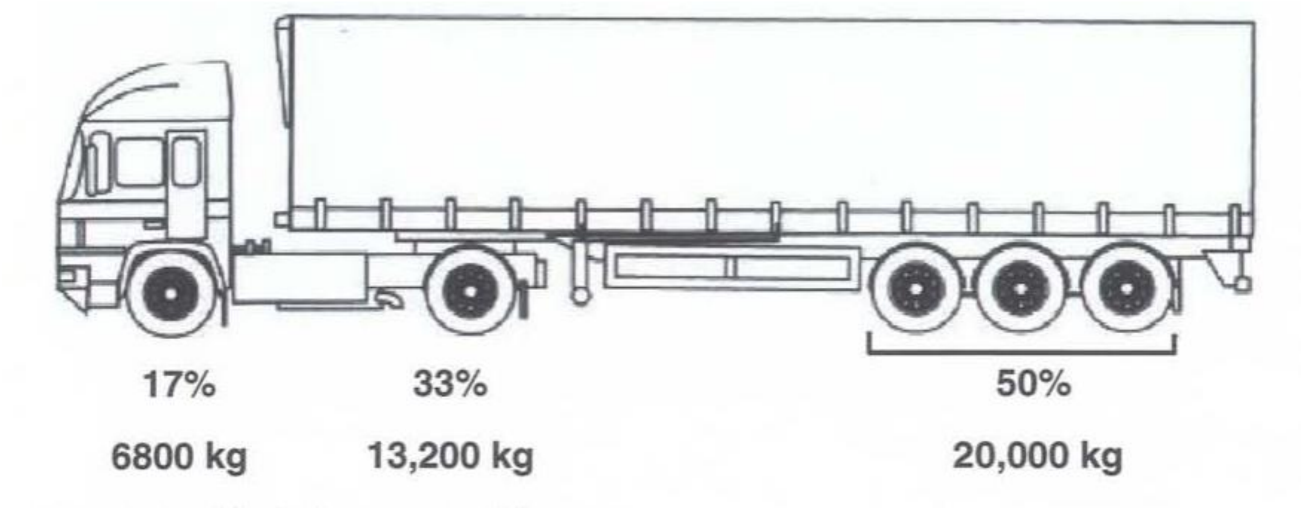


Figure 8: Load distribution on a typical 40-ton truck [7]

The level of tyre wear and the wear profile depend on the axle considered:

- Front axle: free rolling steered axle with only brake torque applied, no lateral acceleration most of the time. The offside tyre wears faster than the nearside tyre due to the combination of the applied camber angle and the road banking,
- Rear axle: driven axle with high accelerating and braking forces applied. When the axle has a dual assembly, the inner shoulders of the inner tyres on both sides wear significantly more than the inner shoulders of the outer tyres due to the axle flexion. Tyre mileage can be improved with the use of braking systems like retarders that can apply a constant braking couple,
- Trailer axles: subject to high level of lateral forces especially the first and third axles since the second, central axle spins around its centre. If the third axle of the trailer is a steering axle, less lateral force is applied which reduces the tyre wear.

4.6 REFERENCES

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5. TYRE PERFORMANCES INTERDEPENDENCY

The most important tyre parameters influencing the tyre wear performance are (see components of a radial tyre in Figure 9 overleaf) [5] [7]:

- The different stiffnesses which determine the shape, stress and slip in the contact patch and depends on the tyre construction (carcass, belt, height to weight ratio, tread pattern and tread compound stiffness),
- The rubber volume available for wear which depends on the tyre size (width and diameter) and the tread design (rubber thickness and tread pattern percentage),
- The tread material characteristics (friction and abrasion).

These tyre parameters also influence other tyre performances such as rolling resistance, braking, wet grip and noise. All these performances are considered antagonistic to each other with the current tyre technologies. Technical innovations are expected to be required to increase tyre wear resistance while maintaining other tyre performances at a high level [4] [6].

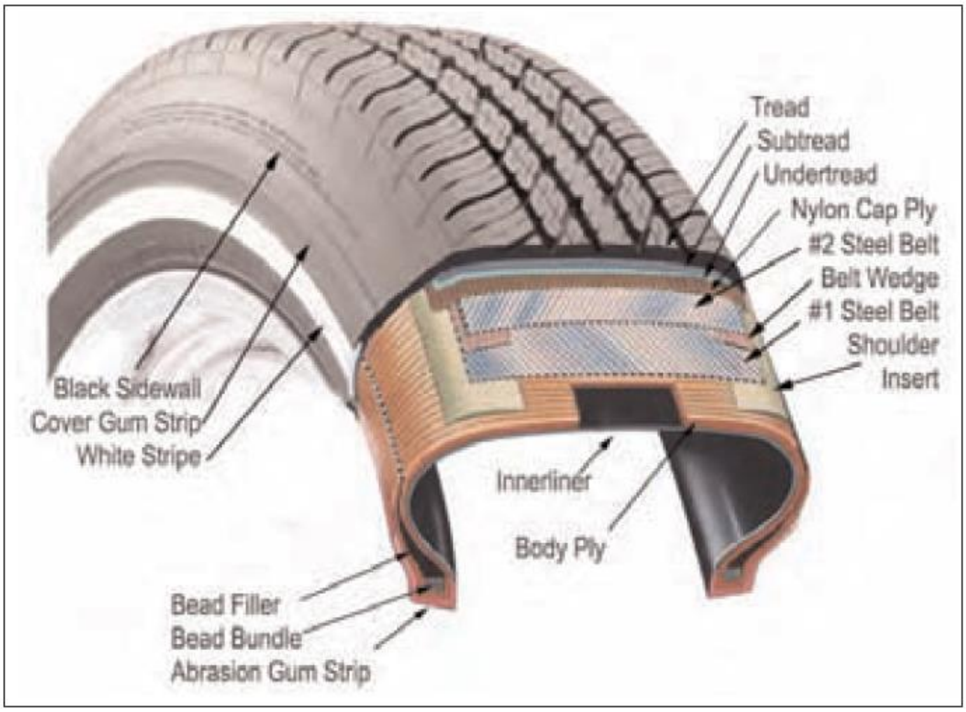


Figure 9: Components of a Radial Tyre [7]

5.1 TYRE ROLLING RESISTANCE

In order to reduce tyre rolling resistance, energy dissipation must be reduced. For that purpose, less hysteretic materials can be used in the tyre tread compound but this compromises the resistance to wear. Silica can be used to overcome the conflict between low rolling resistance and resistance to wear to a certain extent [7].

The Figure 10 overleaf compares the tyre life obtained from a road test simulation for two representative passenger tyre tread compounds:

- an OE SBR (Styrene-Butadiene Rubber) black filled compound,
- a solution SBR / BR (Butadiene Rubber) blend filled with silica.

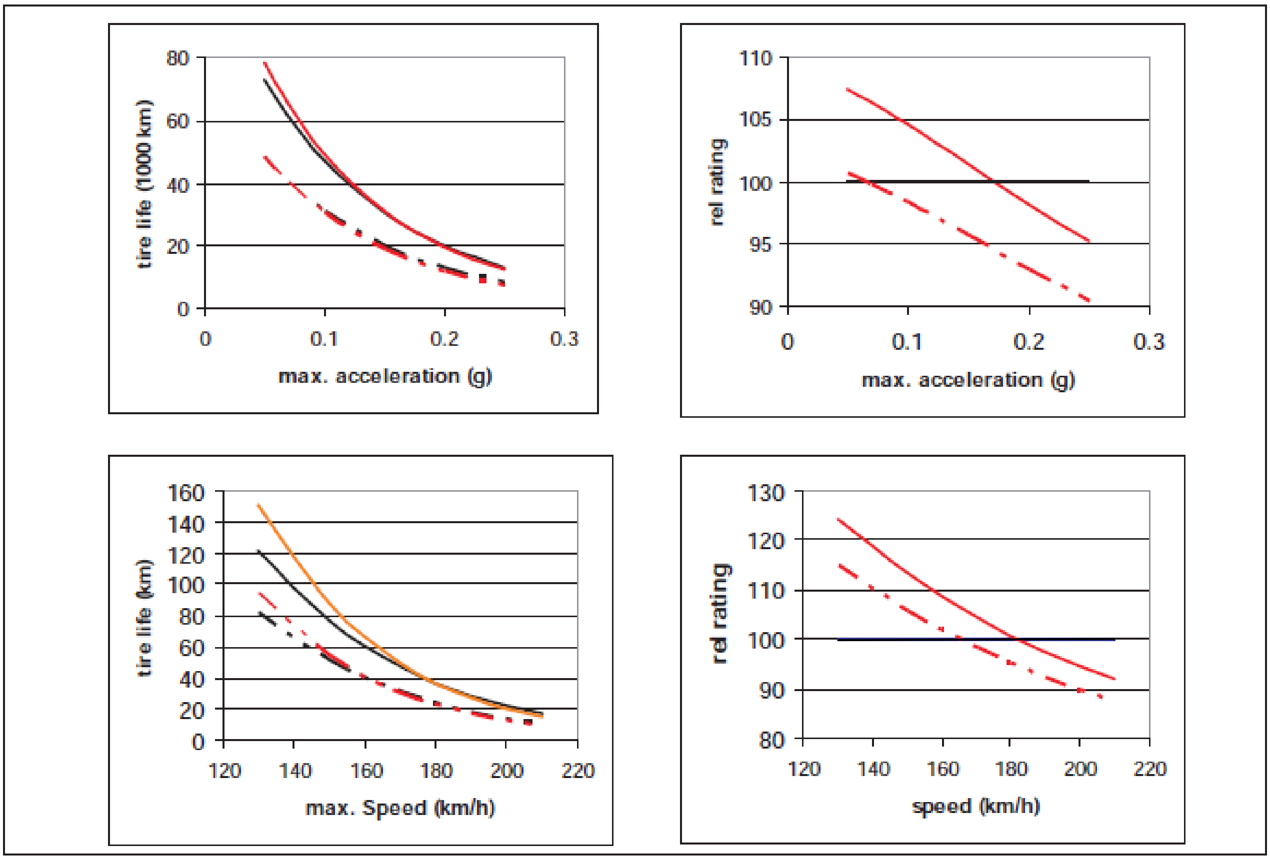
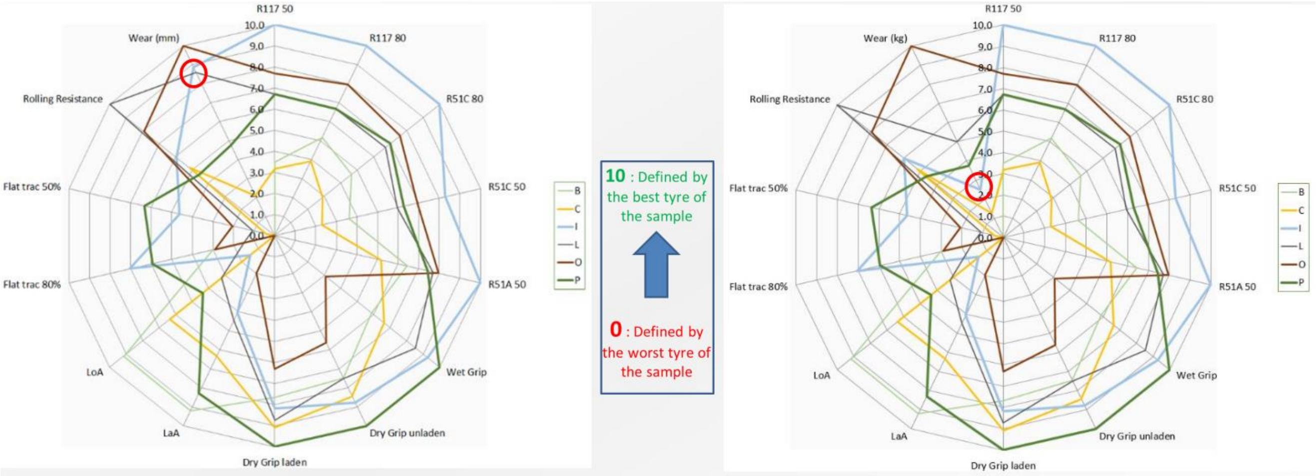


Figure 10: Tyre Life from Road Test Simulation: OE-SBR black filled compound (black) vs solution SBR/BR blend filled with silica (red) – Note: dotted lines refer to a cornering stiffness reduced by a factor of 0.75 vs solid lines. [7]

The two upper graphs show the influence on tyre life as a function of the maximum acceleration of an acceleration distribution function at a constant maximum speed. The two lower graphs show the influence on tyre life when the maximum speed of the speed distribution function is varied and the acceleration is kept constant. As previously described, tyre life decreases rapidly with increasing severity. At low accelerations, the OE-SBR/BR blend + silica is better than the OE-SBR black compound but the rating reverses with increasing acceleration. The same is observed when varying the speed.

As part of their tyre performance study for ACEA, UTAC tested and compared the relative performances of 6 Summer tyres of the same size and service description, 205/55R16 91V. The 6 selected tyres represented a good mix in terms of Rolling Resistance, Rolling Sound, Wet Grip and Handling, as shown in Figure 11 overleaf. They also represented a good mix in terms of tyres brands between Premium and Quality Aftermarket ones [8].



Spider diagram with absolute measurement of groove depth evolution

Spider diagram with absolute measurement of weight evolution

Figure 11: Tyre Performance Study Results [8]

It can be observed that a tyre performing relatively well in wear / abrasion tends to perform well as well in rolling resistance while a tyre performing relatively poorly in wear / abrasion tends to perform poorly as well in rolling resistance. The tyres performing the best in both wear / abrasion and rolling resistance were an OE homologated tyre and an Aftermarket tyre designed for EVs while the worst performing tyre was an aftermarket tyre from the high performance / sport category.

Note: the study relative tyre rankings in terms of wear and abrasion were the same except for one tyre which performed well in wear but relatively poorly in abrasion. This was an aftermarket tyre from a premium brand specifically designed for improved mileage.

5.2 TYRE WET / DRY GRIP AND HANDLING

The tyre tread must provide the necessary grip for driving, braking and cornering in different driving conditions (dry, wet and snow if necessary). This requires a high level of friction the side effect of which tends to be an unwanted high level of wear [7]. At the same time, wider tyres, with an increased stiffness ratio between the tread and carcass, are expected to perform well in handling but also have a lower wear rate compared to narrow tyres. This means that the correlation between a tyre grip and handling performance on one hand and its wear performance, on the other hand, is not straightforward [6].

UTAC study results (see Figure 11) showed that a better grip ability tends to be combined with a more significant wear, especially considering the wear in terms of mass loss, i.e.: abrasion. The tyre performing the best in wear / abrasion but the worst in wet grip was an aftermarket tyre designed for EVs. The tyre performing the best in wet grip but relatively poorly in wear / abrasion is an aftermarket tyre from a premium brand, from a comfort category but with a quite old design compared to the other tyres tested. The OE-homologated tyre performed well in both wet grip and wear and relatively less so in abrasion.

ADAC carried out a tyre performance study on 3 tyres sizes, 185/65R15, 205/55R16 and 225/40R18, covering Summer, All Season and Winter tyres from 2019 to 2022. The tyre wear rates from the study are shown in Figure 12 overleaf [1]:

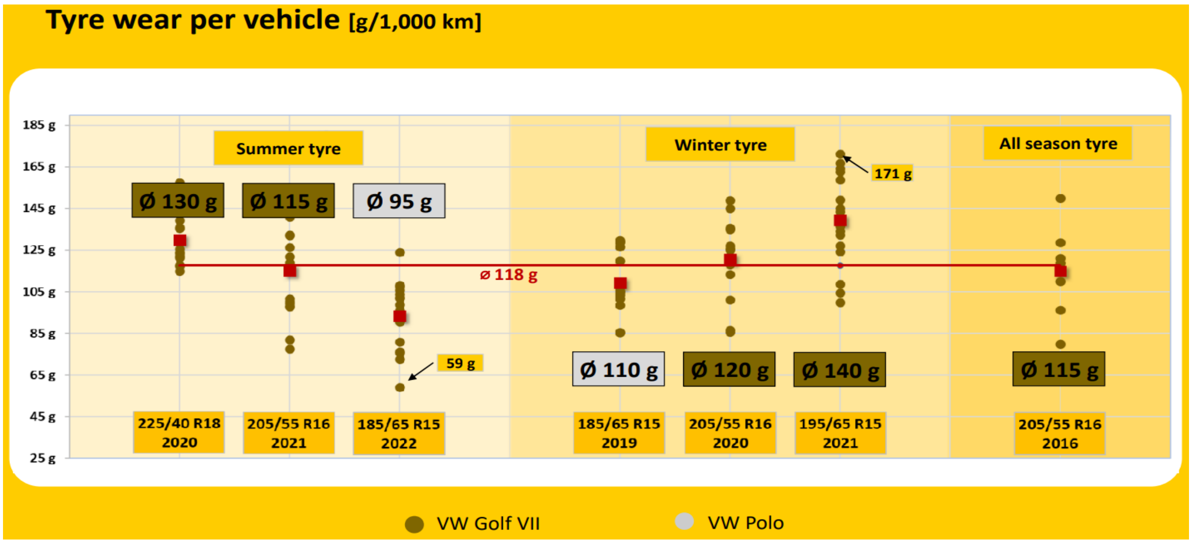


Figure 12: Tyre Wear from Tyre Performance Study [1]

The conclusions of the study were the following:

- Tyres in all dimensions could show a low wear level as well as a good driving safety,
- Tyres with low abrasion were not necessarily linked to an increased risk of aquaplaning,
- Ultra-High Performance (UHP) tyres with above average performance on dry roads tend to have an above average tyre wear as well.

The conclusions of this study were confirmed by another study carried out by ADAC in 2023 covering this time 50 Summer tyres of the same size, 205/55R16 [2] [3].

The results of the different studies considered here show that the main challenge during tyre development is to achieve, at the same time, a high level of tyre wear / abrasion resistance and a high level grip and handling performance. The performances balance reached will likely depend on the development and implementation of innovative technical solutions.

5.3 TYRE ROLLING NOISE

Tyre tread pattern design affects traction, noise and wear in terms of both amount of wear and regularity of the worn profile [7].

The various UTAC and ADAC tyre performance studies, already mentioned, showed a positive correlation between noise and wear: tyres with low tyre wear tend to have advantages in terms of noise level while high noise generation seems to be combined with more wear [1] [2] [3] [8].

In the UTAC study, the best performing tyres in rolling noise and wear were the aftermarket tyre designed for EVs and the aftermarket tyres from a premium brand designed for improved mileage. The worst performing tyres were aftermarket tyres from the high performance / sport category.

5.4 SNOW PERFORMANCE

With regards to 3PMSF tyres designed for severe snow conditions, they have a special formulated tread compound with a higher natural rubber content in order to have better grip and handling at low temperature (below 7°C). They also have a special tread design with sipes in their tread blocks as well as an increased tread depth to have better traction on snow and ice [7].

The ADAC tyre performance study covering Summer, All Season and Winter tyres showed no general differences in terms of tyre wear although the Summer tyres tends to have a slightly lower wear than the Winter tyres of the same size [1].

5.5 HDVs TYRE PERFORMANCES

Truck tyres only use natural rubber to improve longevity and rolling resistance while passenger car tyres also include synthetic rubber to improve adherence [4].

No specific truck tyres performances study has been found during this literature review.

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6. TYRE WEAR / ABRASION TESTING

6.1 TYRE WEAR / ABRASION TEST APPROACH

A tyre wear / abrasion test method should be representative of real driving conditions, repeatable, reproducible and cost efficient.

To have a repeatable and valid test method, all the factors influencing tyre wear / abrasion rate should be under control [3]:

- Tyre load,
- Tyre solicitation and usage,
- Road surfaces,
- Ambient temperature and climate.

Traditionally, the wear / abrasion rate of a tyre has been evaluated on a vehicle driven at prescribed speeds on a known test route in a relative manner to a known reference tyre to mitigate the impact of outside parameters: climatic conditions, road surfaces, vehicle, traffic and driving style. The tyre wear rate is measured in tread depth loss per distance travelled (mm/km) while the abrasion rate is measured in mass loss per distance travelled (g/km) [3] [18].

The evolution of the tyre wear / abrasion during its life changes from tyre to tyre. The wear / abrasion rate ranking between two tyres can change during a test. This means that a minimum test running distance should be defined to ensure stable results and get a correct separating power [1] [4].

6.1.1 TYRE WEAR VS TYRE ABRASION

Tyre wear in terms of tread depth loss is not necessarily correlated with tyre abrasion in terms of material loss [19].

The wear performance of a tyre is its ability to reach a high mileage. This mileage, or service life, is defined as the mileage run until a point on the tread has reached the legal limit of the wear indicator. A tyre mileage depends on the tyre abrasion rate, the amount of rubber available to wear and the regularity of the transversal worn profile. A tyre irregular wear profile can significantly reduce a tyre service life or mileage. Irregular wear patterns depend on several external factors such as [18]:

- Vehicle suspension geometry,
- Vehicle misalignment,
- Driving factors: rapid acceleration / braking, high speed cornering,
- Under-inflation and over-inflation.

This means that, for tyre wear testing, the specification of the vehicle alignment setting is of paramount importance and should be much more stringent than for abrasion testing. This also means that, to be able to extrapolate tyre mileage from tyre wear testing, the test must run for longer to get a stabilized value compared to an abrasion test. For tyre abrasion, the test running distance is expected to be at least 8,000km while for tyre wear, the test running distance is expected to be at least 15,000km [8].

With regards to tyre wear particle emission, the relevant indicator is the quantity of rubber release for a given distance which corresponds to the tyre abrasion rate [8] [11] [13].

6.1.2 VEHICLE VS DRUM TEST METHOD

With regards to vehicle test method, comparison tests between test tyres and a reference tyre are conducted using vehicle convoys to mitigate environmental factors, differences in road surfaces and other variables. The vehicles are driven along a defined test route on public roads with a given driving severity [3] [18].

For tyre wear testing, the test tyres and the reference tyres must be the same size and all the vehicles within the convoy must be identical with the same settings. For abrasion testing, different tyre sizes on different vehicles can be tested although all the vehicles within the convoy should have the same type of powertrain and architecture [6].

During a test, driver permutation can be done between the vehicles, vehicles position can be permuted within the convoy and tyres can be permuted between the vehicles. Tyres position on one vehicle can be permuted as well. This is to ensure that all the tyres, including the reference one, experience the same conditions [6] [20]:

- Weather,
- Road conditions,
- Speed and accelerations,
- Positions and drivers in the convoy.

The Uniform Tire Quality Grading (UTQG), implemented by the U.S. Federal Government in 1979, includes a treadwear grade determined by tyre manufacturers The treadwear grade is based on vehicle test results [18].

During a vehicle wear / abrasion test, many variance factors are not possible or difficult to control. It also requires the definition of a specific test route at a specific location. Vehicle tests in real traffic can be complex and time / cost intensive. They may also pose a safety risk for the drivers and other road users. An alternative to vehicle testing is testing on a drum test machine in a laboratory [1]. An example of a such a test machine is shown in Figure 13 overleaf:

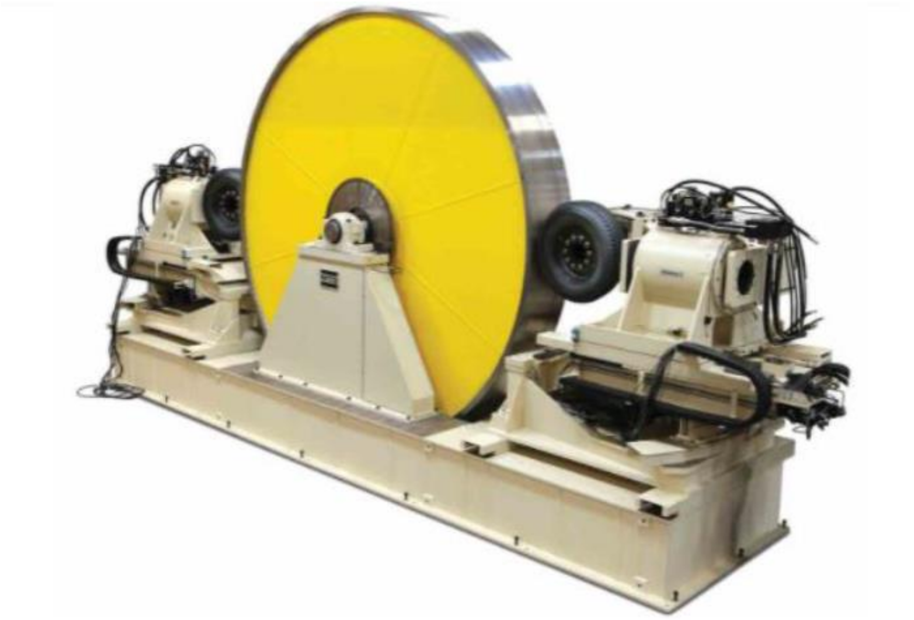
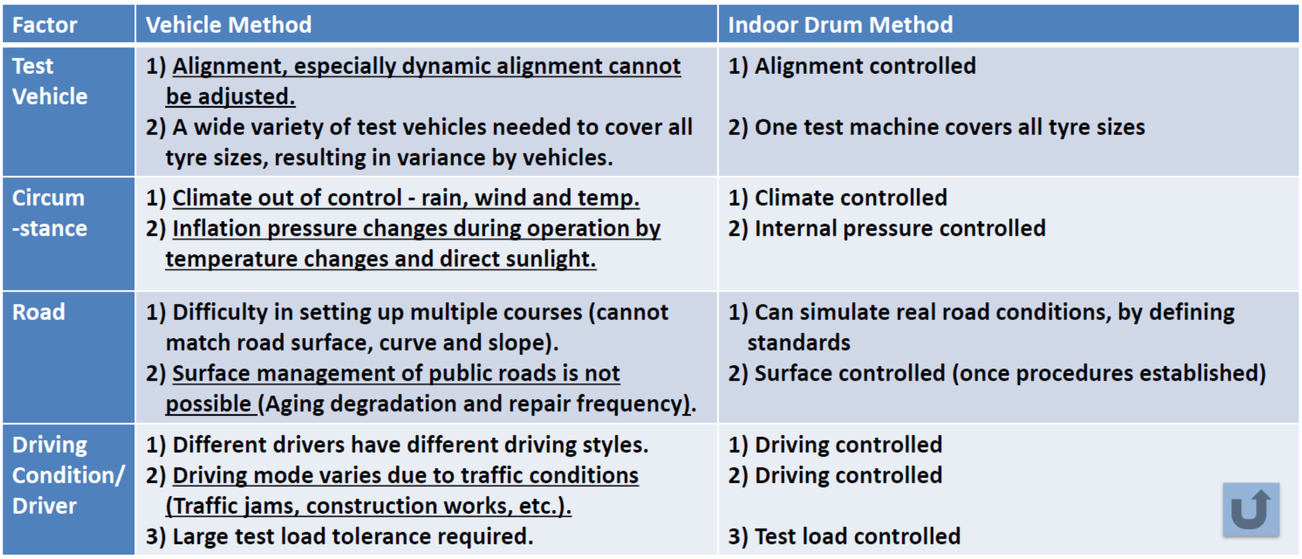


Figure 13: MTS Tyre Treadwear Test Machine [13]

Beyond the initial investment required to purchase and install a drum test machine, drum testing can allow for cost effective, repeatable and reproducible testing as the wear / abrasion influencing parameters can be controlled (see Figure 14 below):



Factor	Vehicle Method	Indoor Drum Method
Test Vehicle	1) Alignment, especially dynamic alignment cannot be adjusted. 2) A wide variety of test vehicles needed to cover all tyre sizes, resulting in variance by vehicles.	1) Alignment controlled 2) One test machine covers all tyre sizes
Circum -stance	1) Climate out of control - rain, wind and temp. 2) Inflation pressure changes during operation by temperature changes and direct sunlight.	1) Climate controlled 2) Internal pressure controlled
Road	1) Difficulty in setting up multiple courses (cannot match road surface, curve and slope). 2) Surface management of public roads is not possible (Aging degradation and repair frequency).	1) Can simulate real road conditions, by defining standards 2) Surface controlled (once procedures established)
Driving Condition/ Driver	1) Different drivers have different driving styles. 2) Driving mode varies due to traffic conditions (Traffic jams, construction works, etc.). 3) Large test load tolerance required.	1) Driving controlled 2) Driving controlled 3) Test load controlled

Figure 14: Tyre Wear / Abrasion Testing - Vehicle vs Drum Test Method [13]

The main challenge with drum testing is to be able to specify all the test conditions for them to be representative of the variety of the real-world conditions encountered and not restrict them so much as to give results that would not be aligned with what could be expected in a real usage.

6.2 DRIVING CONDITIONS

6.2.1 DRIVING SEVERITY CHARACTERISATION

A tyre service life depends on the conditions in which it is used in terms of driving conditions and geographical area. In a specific market, the wear performance of a vehicle / tyre combination can be described by a statistical distribution of the tyre mileages. This is a lognormal distribution as shown in Figure 15 below:

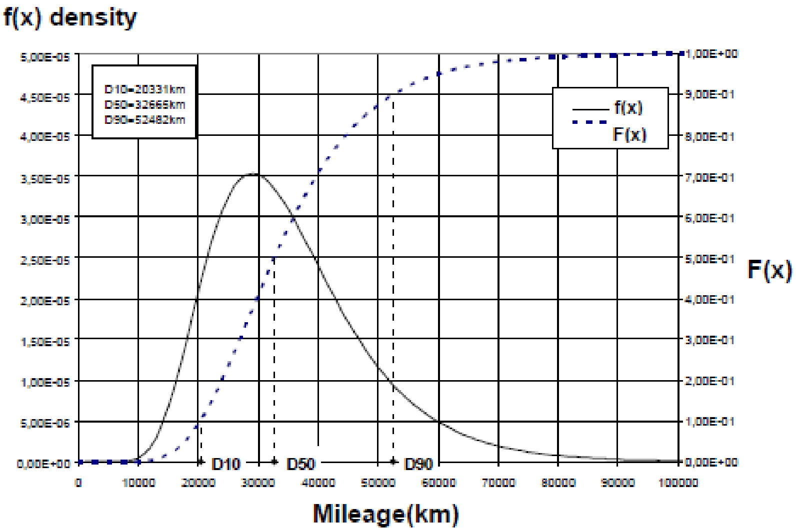


Figure 15: Customer Mileage Distribution [16]

The curve F(x) shows the percentage of drivers whose tyres have a mileage shorter than x. The derivative curve f(x) shows the probability a specific driver has of reaching a certain mileage. Three points on the F(x) curve are currently used:

- D10 (first percentile) represents severe use: 90% of the drivers will reach at least this mileage,
- D50 (median) represents moderate use: 50% of the drivers will reach at least this mileage,
- D90 represents mild use: 10% of the drivers will reach at least this mileage.

Usually, tyres are designed around the D50 but tyre evaluation can be done by comparing the D10, D50 and D90 values as some inversion in tyre performance may occur between these 3 points of the distribution.

To quantify the severity of use, the longitudinal and lateral accelerations at the vehicle’s centre of gravity are measured along with the forward velocity when the vehicle is driven over the road, its course. Both longitudinal and lateral accelerations can be described by a statistical distribution function, symmetrical around zero. It can be approximated by a normal distribution. This means that their width is defined by 3 times their standard deviation (σ) and includes 99.9% off all events [18]. To illustrate this, the lateral and longitudinal accelerations distribution corresponding to the European driving styles, based on ETRTO EU usage database, is shown in Figure 16 overleaf:

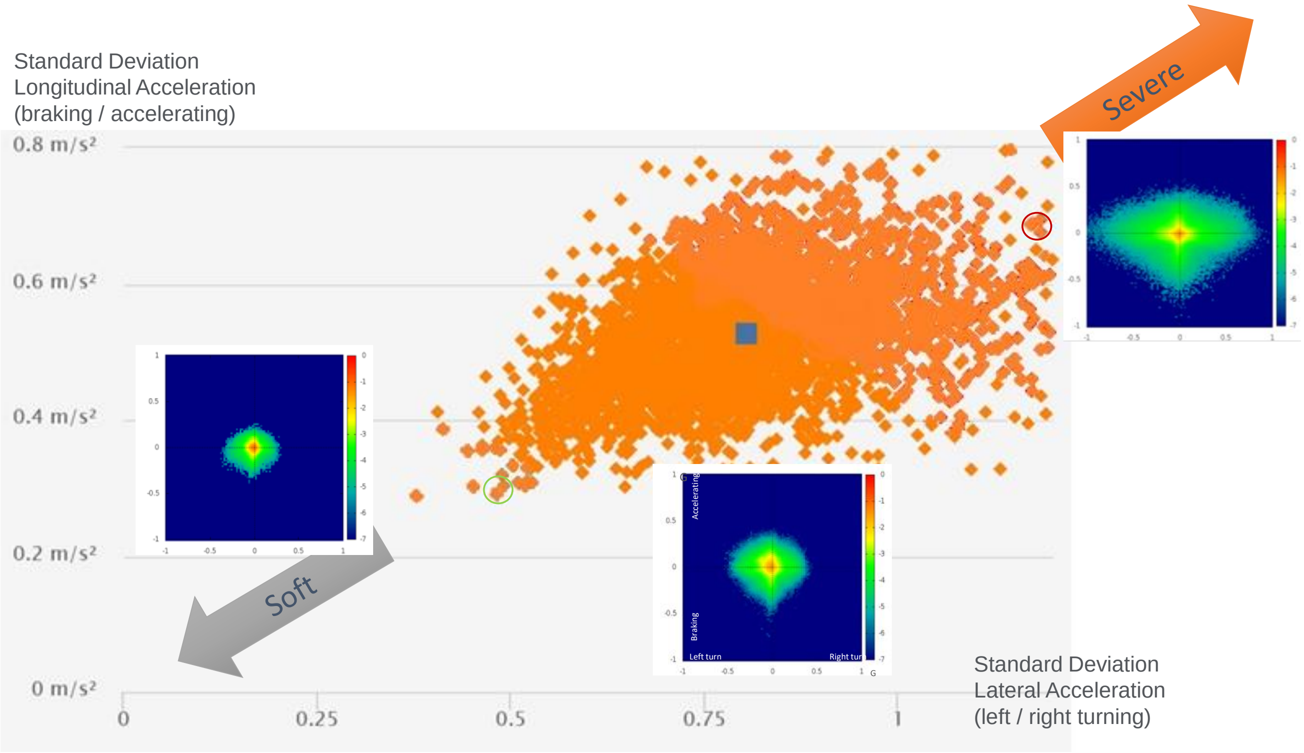


Figure 16: Distribution of European driving styles [5]

Each point on the graph represents the range, ie: standard deviation, of the lateral and longitudinal accelerations for one single vehicle over several tens of thousands of kilometres.

With regards to vehicle wear testing, a specific circuit can be defined to provide the same lateral and longitudinal acceleration ranges, representative of a given level of severity in a given market.

Based on the same characterisation principles but applied to a specific test circuit used for vehicle wear testing, a device called Driving Severity Monitor was developed by Veith in the 1980s to characterize a specific route / vehicle / driver system in terms of driving severity. It uses recorded values of lateral and longitudinal accelerations as well as velocity (once per revolution) and travelled distance to calculate a special single value called a Driving Severity Number, DSN. The Figure 17 overleaf illustrates how tyre wear rates are shown to correlate with the measured DSN for four test circuits:

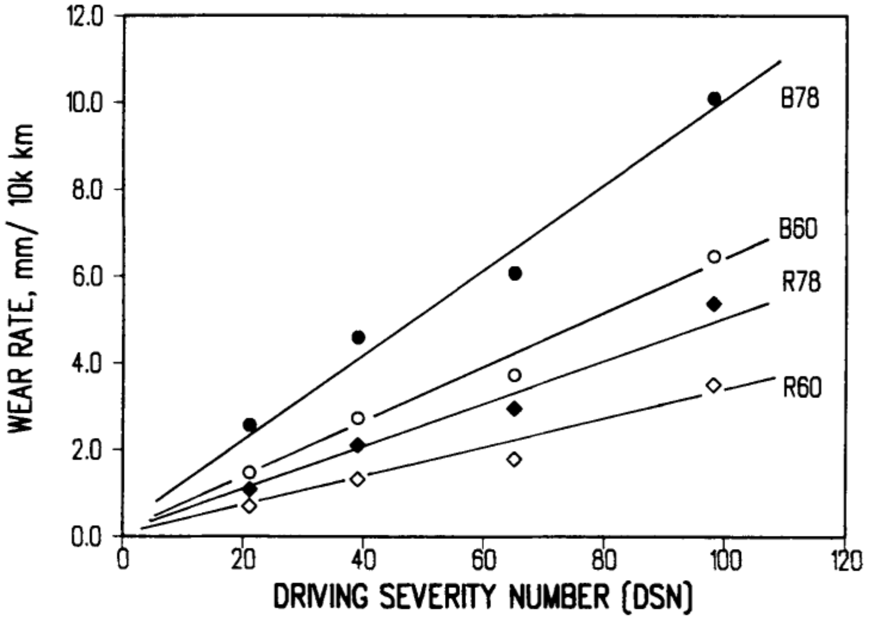


Figure 17: Rate of Wear at Automotive Proving Grounds vs Driving Severity Number (DSN for 4 types of tyres, R= Radial, B = Bias, 60, 78 = aspect ratios [21]

This Driving Severity Monitor may be used to compare different test circuits together but cannot assess them in terms of real-world driving severity representativeness [12].

With regards to drum wear testing, the accelerations and velocity data need to be converted into tyre forces to be used as input signals [18]. This is done using vehicle dynamics models as described in Figure 18 below:

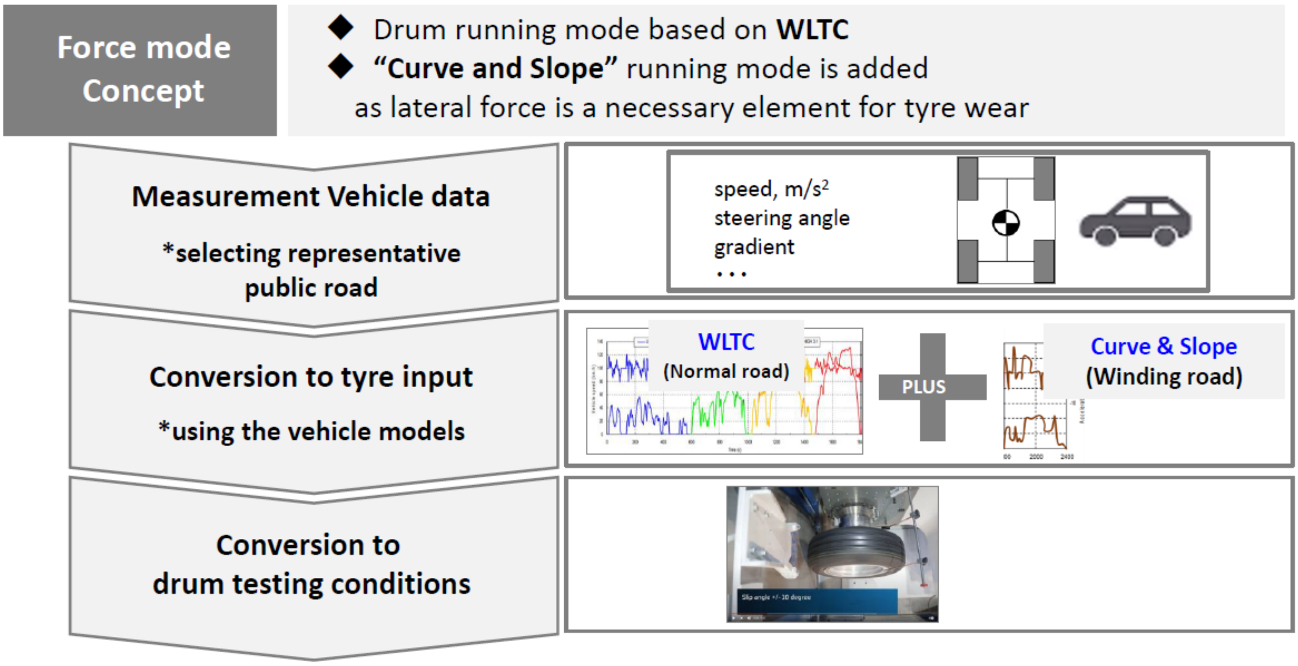


Figure 18: Converting vehicle driving conditions into indoor drum test conditions [15]

6.2.2 DRIVING CONDITIONS REPRESENTATIVENESS

To be representative of real-world driving conditions, a circuit used for tyre wear / abrasion testing should be specified in terms of [3] [16] [18]:

- Road type mix: urban, rural, highway,

- Longitudinal and lateral accelerations histograms,
- Speed range.

This means that these data should be first determined for the targeted market(s) and then the circuit should be defined to match them. As an example, the representative data of real driving in European market are shown in Figure 19 below:

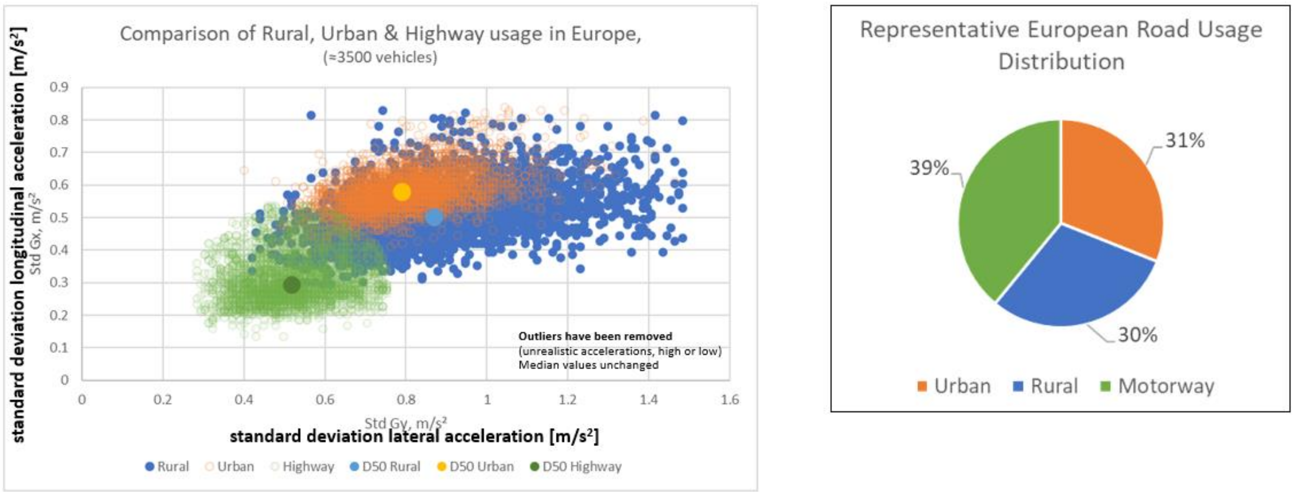
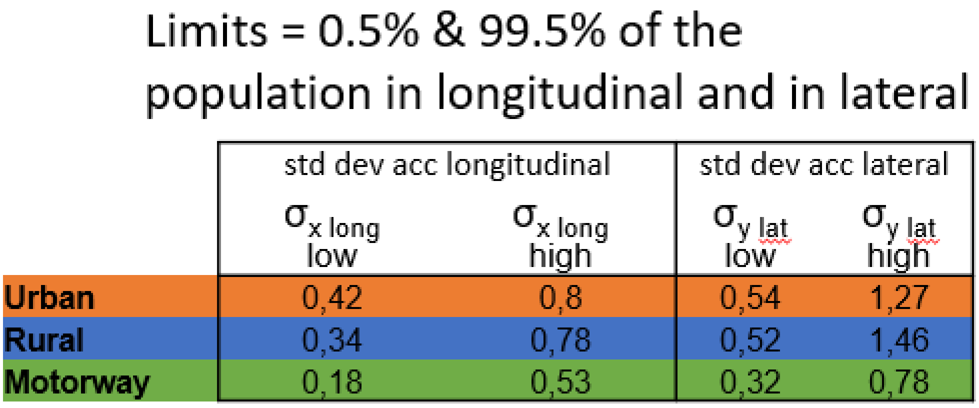


Figure 19: European Market Representative Data – Road Type & Acceleration Levels [6]

Typical acceleration levels can be determined for each road type as shown in Figure 20 below:



Limits = 0.5% & 99.5% of the population in longitudinal and in lateral

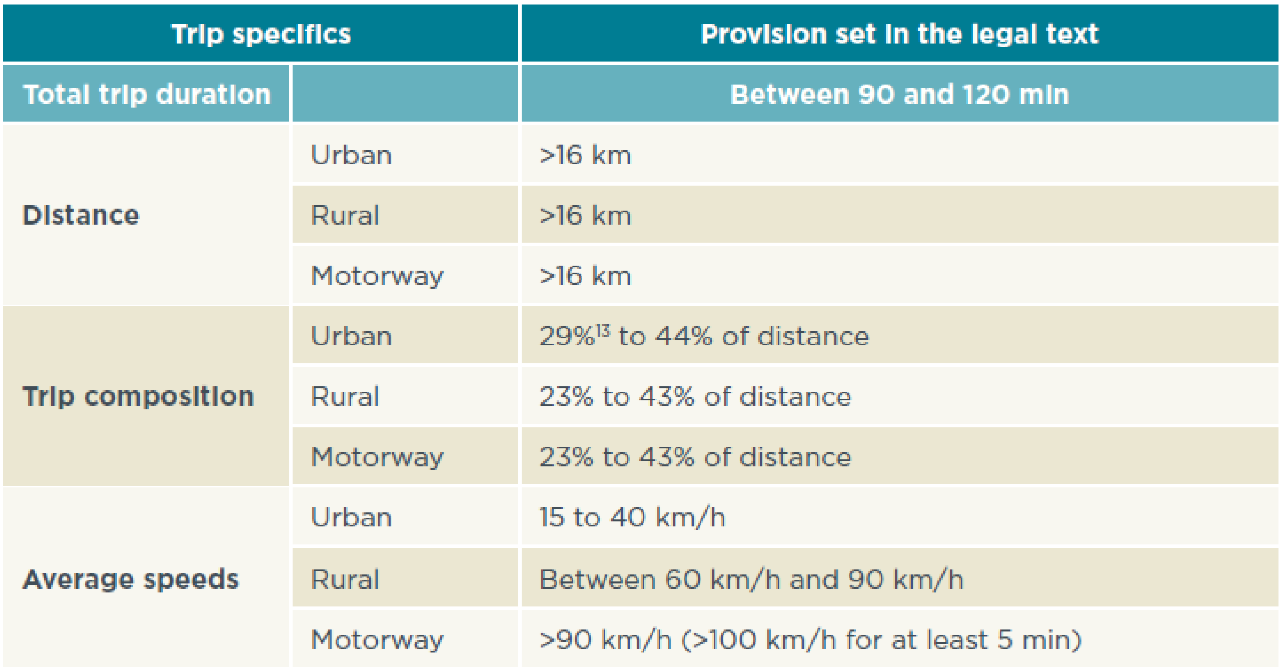
	std dev acc longitudinal		std dev acc lateral	
	$\sigma_{x\ long}$ low	$\sigma_{x\ long}$ high	$\sigma_{y\ lat}$ low	$\sigma_{y\ lat}$ high
Urban	0,42	0,8	0,54	1,27
Rural	0,34	0,78	0,52	1,46
Motorway	0,18	0,53	0,32	0,78

Figure 20: European Market Representative Data – Acceleration Levels per Road Type [6]

To be representative, the wear / abrasion test should include an urban section, however, urban areas are prone to disturbed traffic conditions which prevents a good test repeatability in terms of acceleration values. The solution considered is to emulate the urban road section with country roads since urban acceleration conditions are almost completely covered by rural ones (see Figures 19 and 20) [2] [6].

With regards to existing test cycle representative of real word driving conditions and already endorsed by various countries around the world, the Real Driving Emissions (RDE) test procedure and the Worldwide Harmonized Light Vehicle Test Cycle (WLTC) could be considered, respectively, for vehicle and laboratory testing [1] [3] [13].

With regards to vehicle testing, the RDE test procedure for Light Duty Vehicles is conducted on open roads and covers a broad range of driving conditions typical of the European market. It includes a mix of road types (urban, rural and motorway) the definition of which are based on speed as shown in Figure 21 overleaf:



Trip specifics		Provision set in the legal text
Total trip duration		**Between 90 and 120 min**
Distance	Urban	>16 km
	Rural	>16 km
	Motorway	>16 km
Trip composition	Urban	29%[13] to 44% of distance
	Rural	23% to 43% of distance
	Motorway	23% to 43% of distance
Average speeds	Urban	15 to 40 km/h
	Rural	Between 60 km/h and 90 km/h
	Motorway	>90 km/h (>100 km/h for at least 5 min)

Figure 21: RDE Test Distance and Speed Specifications [10]

The RDE test dynamic boundary conditions are shown in Figure 22 below (RPA: Relative Positive Acceleration for urban, rural and motorway/expressway shares):

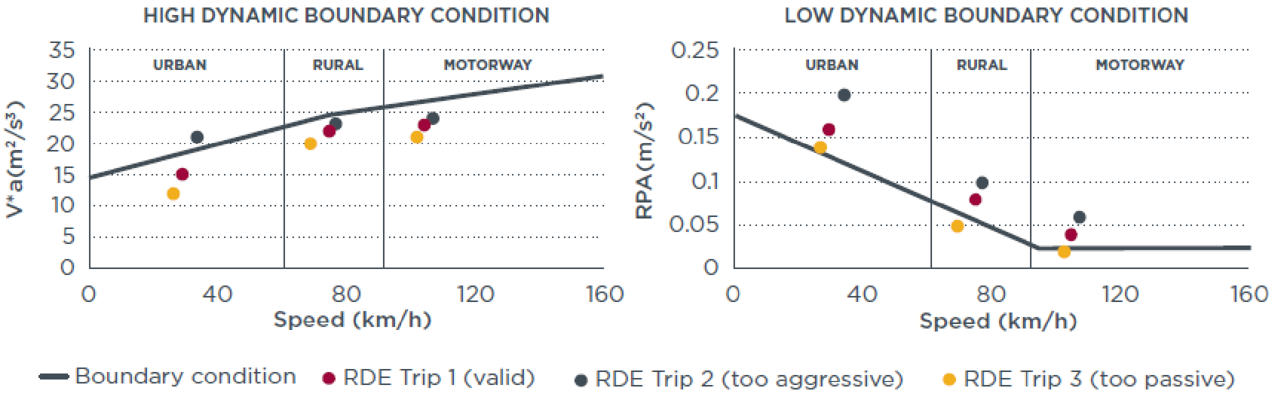


Figure 22: Dynamic boundary conditions with three illustrative RDE trips [10]

To be able to consider the RDE test procedure for tyre wear / abrasion testing purpose, its distance would need to be increased to a minimum of 300km to cover a wide enough range of different roads types and surfaces. Typical wear circuits length is between 300 and 600 km [20]. The dynamic boundary conditions would also need to be refined to consider lateral accelerations as well as longitudinal ones [3].

With regards to laboratory testing, the WLTC could be used with regards to tyre longitudinal solicitations, however, it would need to be complemented with an additional test cycle representative of tyre lateral solicitations [13].

6.3 ROAD SURFACE

Road surface influences tyre wear / abrasion by a factor from 2 to 3 especially through its micro-roughness [11] [16].

With regards to vehicle testing, road surface texture could be characterised over the total length of the circuit defined but it can be considered that the average structure of a test route is likely to reflect the average of a whole geographical area and that the difference between two different test routes is likely to be smaller than the differences encountered along each route separately [17] [18].

With regards to laboratory testing, the drum surface needs to be specified in terms of material and texture in order to be representative of real-world conditions, as described in the Figure 23 below:

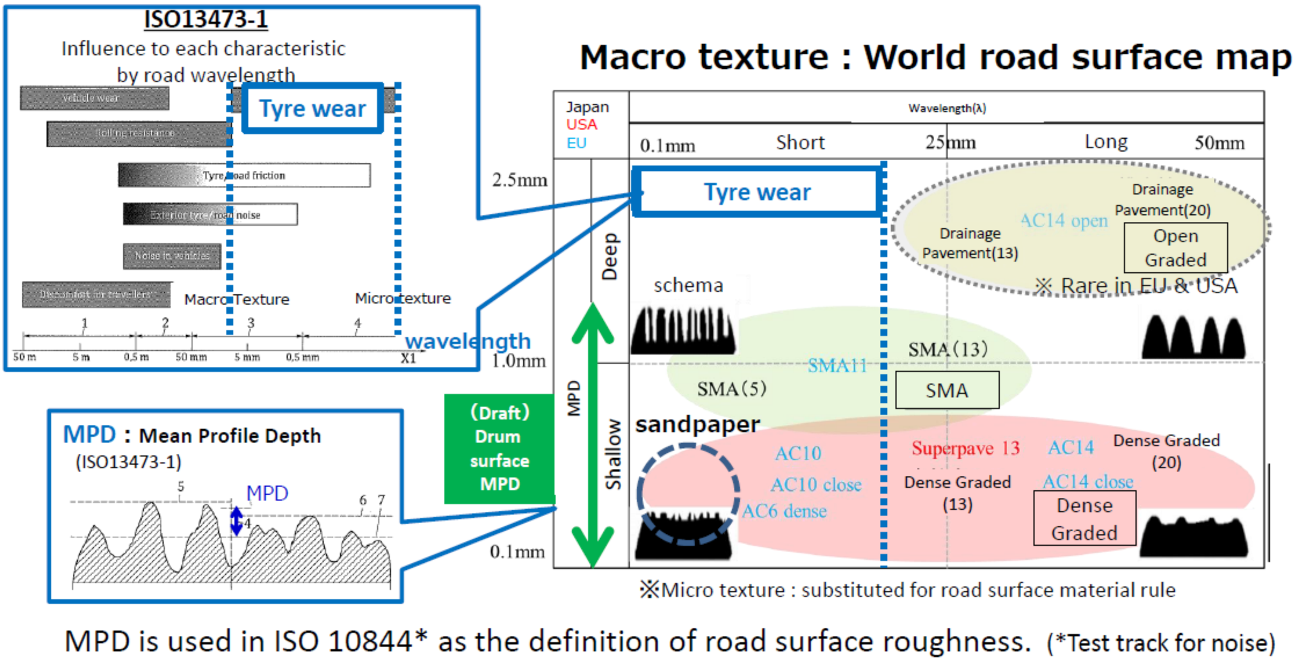
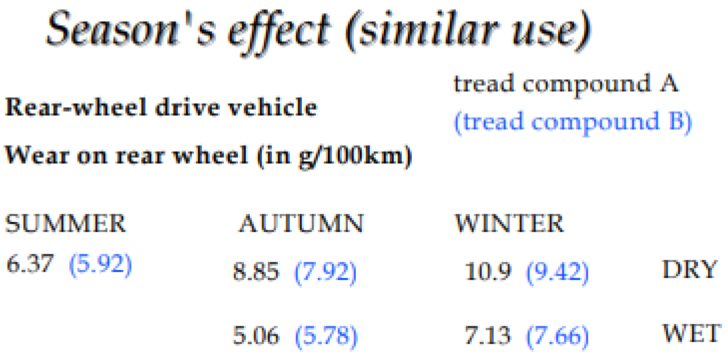


Figure 23: Mapping World Road Surface Mapping for Drum Surface Definition [14]

The drum surface should be durable enough to not influence test results and de-gumming method should be used to prevent tyre adhesion which would change the test surface during a test [14].

6.4 AMBIENT WEATHER CONDITIONS

Ambient conditions such as temperature and humidity influence the tyre / road surface interface characteristics and therefore the tyre wear. Tyre wear may vary by a factor of 1 to 2 depending on the weather conditions (seasons and wet / dry surface), as shown in Figure 24 below:



Season's effect (similar use)

Rear-wheel drive vehicle

Wear on rear wheel (in g/100km)

tread compound A
(tread compound B)

SUMMER	AUTUMN	WINTER	
6.37 (5.92)	8.85 (7.92)	10.9 (9.42)	DRY
	5.06 (5.78)	7.13 (7.66)	WET

Figure 24: Seasonal Effects on Tyre Wear [16]

The variations are linked to the impacts on the surface texture and the rubber compound.

Due to their special formulated tread compound, Winter (3PMSF) tyres have a different temperature sensitivity from Summer (non 3PMSF) tyres. This different temperature sensitivity should be considered when specifying the test ambient temperature range for the test validity as well as the choice of the reference tyre. For vehicle testing, this can impact the choice of the circuit location and / or the period during the year when the tests are performed: for instance, different locations could be chosen to test non 3PMSF and 3PMSF tyres or the same location could be chosen for both but non 3PMSF tyres tests could be performed during the summer months while the 3PMSF tyres tests could be performed during the winter months [3] [4] [6] [16] [19].

For vehicle testing, the maximum percentage distance allowed in the rain should also be specified to limit the influence on the test results [20].

6.5 HDVs TYRES WEAR / ABRASION TESTING

With regards to HDVs tyre testing, the parameters discussed above are all still valid and should be specified to be representative of HDVs applications specificities in terms of [11] [17]:

- Circuit road type mix,
- Driving conditions,
- Running distance,
- Vehicle load conditions,
- Vehicle axles configuration,
- Rubber compound vs seasonality effect.

As mentioned previously, long haul trucks mainly operate on motorways with low levels of acceleration with their tyres designed to have a long service life. Finding a suitable circuit representative in terms of driving severity but which does not require to run the test for an excessively long period of time may be challenging [17].

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7. TYRE & ROAD WEAR PARTICLES (TRWP) EMISSIONS

7.1 TRWP CONTRIBUTION TO NON-EXHAUST PATRICLES EMISSIONS

Traffic related sources of Particulate Matter (PM) are a significant contributor to air pollution especially in urban environments. They can be distinguished into two main categories: exhaust and non-exhaust emissions. The main sources of non-exhaust emissions are [1] [8]:

- Brake wear (16-55%),
- Tyre wear (5-30%),
- Road dust resuspension (28-59%).

It has been estimated that exhaust and non-exhaust emissions were contributing equally to traffic related PM emissions. However, due to ever stricter regulations on exhaust emissions, the proportion of exhaust emissions have decreased in recent years. It is expected that non-exhaust emissions will soon represent 90% of traffic related PM emissions [8] [9] [15].

The tyre wear process generates and releases elongated “sausage-like” particles that are actually aggregates of tyre tread fragments and mineral elements from the road surface. They are called Tyre & Road Wear Particles (TRWP). They are made of 40-60% of road materials like asphalt and concrete but they are usually categorised as microplastics since the elastomers in tyres are considered to be a type of the different polymers which are the main ingredients of other plastics and microplastics. TRWP density is in the range of 1.2 to 1.7 g/cm^3 compared to 0.9 to 1.4g:cm^3 for usual microplastics [4] [10] [11] [12] [15]

Tyres are a mixture of natural and synthetic rubbers (for passenger car tyres). Carbon black is used as filler but it is sometimes replaced by Silica to improve rolling resistance. Zinc (Zn) and Sulphur (S) are used as vulcanization agents during the tyre manufacturing process. Tyre wear PM10 presents a high concentration of Zn as well as Copper (Cu), S and Silicon (Si). The ultrafine particles below 0.1 µm are heterogenic and seem to originate from organic constituents of tyres (maybe also sulphur) [8] [10] [11] [15].

7.2 TYRE WEAR EMISSION FACTOR (EF)

Air quality modelling and emission monitoring over time, for a specific country, are based on PM emissions estimations for each source, including tyre wear. Tyre wear particle emissions are estimated, for each type of vehicles (passenger cars, heavy duty vehicles, motorcycles, etc), using standardised Emission Factors (EF) combined with vehicle driven distances statistics [4] {15].

Emission Factors can be expressed as a quantity emitted per km per vehicle, in mg/km/vehicle. For tyre wear, typical values are as follow [10]:

- Passenger cars: 50 - 132 mg/km/vehicle,
- Light commercial vehicles: 102 - 320 mg/km/vehicle,
- Trucks: 546 - 1500 mg/km/vehicle,
- Buses: 267 - 700 mg/km/vehicle,
- Motorcycles: 39 - 47 mg/km/vehicle.

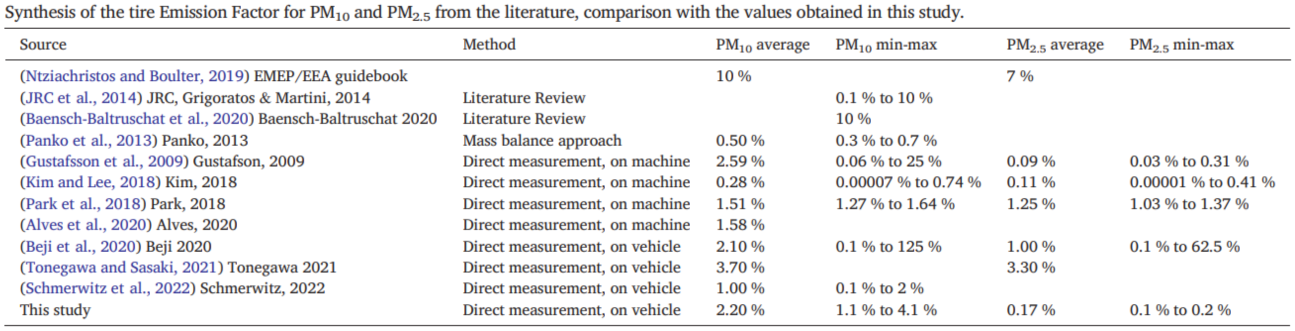
For a passenger car, a typical wear rate of the order of 112mg/km corresponds to a mass loss of 1.4kg over a distance of 50,000km [16].

Emission Factors have different values for PM10 (particle diameter less than 10µm), PM2.5 (particle diameter less than 2.5µm) and Total Suspended Particles (TSP), i.e.: all suspended particles whatever their size. Reported values for tyre wear PM10 are in the range of 4 to 13 mg/km/vehicle for Light Duty Vehicles (LDV). The values reported for Heavy Duty Vehicles (HDV) are one order of magnitude higher compared to LDV [8].

For tyre wear, most countries currently use the Emission Factors methodology and data from the EMEP/EEA Air Pollutant Emissions Inventory Guidebook (EMEP/EEA, 2019). The tyre wear data in the guidebook were established from a literature review of studies published between 1995 and 2002 and based on indirect estimation of TSP and PM10 from tyre wear rate [1] [4]. Indirect estimations can be based on the following methods [4] [13]:

- Measurement of total tyre mass loss / tread depth loss after the tyre has been driven over a given distance,
- Measurement of airborne vehicle emissions in a tunnel or next to roads.

Indirect estimations tend to overestimate the tyre wear EF by including non tyre wear emissions in the tyre wear fraction. More recent studies based on direct measurement of the tyre wear particles airborne fraction during vehicle or laboratory testing tend to give lower values than the guidebook ones, as shown by Charbouillot et al. in their study (see Figure 25 below):



Synthesis of the tire Emission Factor for PM_{10} and $PM_{2.5}$ from the literature, comparison with the values obtained in this study.

Source	Method	PM_{10} average	PM_{10} min-max	$PM_{2.5}$ average	$PM_{2.5}$ min-max
(Ntziachristos and Boulter, 2019) EMEP/EEA guidebook		10 %		7 %	
(JRC et al., 2014) JRC, Grigoratos & Martini, 2014	Literature Review		0.1 % to 10 %		
(Baensch-Baltruschat et al., 2020) Baensch-Baltruschat 2020	Literature Review		10 %		
(Panko et al., 2013) Panko, 2013	Mass balance approach	0.50 %	0.3 % to 0.7 %		
(Gustafsson et al., 2009) Gustafson, 2009	Direct measurement, on machine	2.59 %	0.06 % to 25 %	0.09 %	0.03 % to 0.31 %
(Kim and Lee, 2018) Kim, 2018	Direct measurement, on machine	0.28 %	0.00007 % to 0.74 %	0.11 %	0.00001 % to 0.41 %
(Park et al., 2018) Park, 2018	Direct measurement, on machine	1.51 %	1.27 % to 1.64 %	1.25 %	1.03 % to 1.37 %
(Alves et al., 2020) Alves, 2020	Direct measurement, on machine	1.58 %			
(Beji et al., 2020) Beji 2020	Direct measurement, on vehicle	2.10 %	0.1 % to 125 %	1.00 %	0.1 % to 62.5 %
(Tonegawa and Sasaki, 2021) Tonegawa 2021	Direct measurement, on vehicle	3.70 %		3.30 %	
(Schmerwitz et al., 2022) Schmerwitz, 2022	Direct measurement, on vehicle	1.00 %	0.1 % to 2 %		
This study	Direct measurement, on vehicle	2.20 %	1.1 % to 4.1 %	0.17 %	0.1 % to 0.2 %

Figure 25: Tyre Emission Factor for PM10 and PM2.5 - Literature Review – Note: PM2.5 and PM10 EFs expressed as percentage of tyre mass loss rate [4].

7.3 TRWP EMISSION TESTING METHODOLOGIES

To reduce the uncertainty over tyre wear Emission Factors, direct measurement of TRWP emission either on a vehicle or in a laboratory should be considered. All the aspects from the TRWP particles generation to their quantification should be carefully considered [6] [8]:

- The methodology used to generate the TRWP should be representative of real-world usage for different types of vehicles,
- The sampling system efficiency and robustness should allow the collection of the relevant range of particle sizes to allow for a comprehensive particle size distribution analysis,
- The method used to identify and quantify the TRWP collected should be accurate enough to avoid, or at least minimize, any underestimation or overestimation.

The direct measurement methods considered here are [3]:

- Vehicle open road testing,
- Vehicle closed track testing,
- Laboratory testing.

7.3.1 VEHICLE OPEN ROAD TESTING

An example of a vehicle based TRWP measurement set up that was used for open road and closed track testing is shown in Figure 26 below:

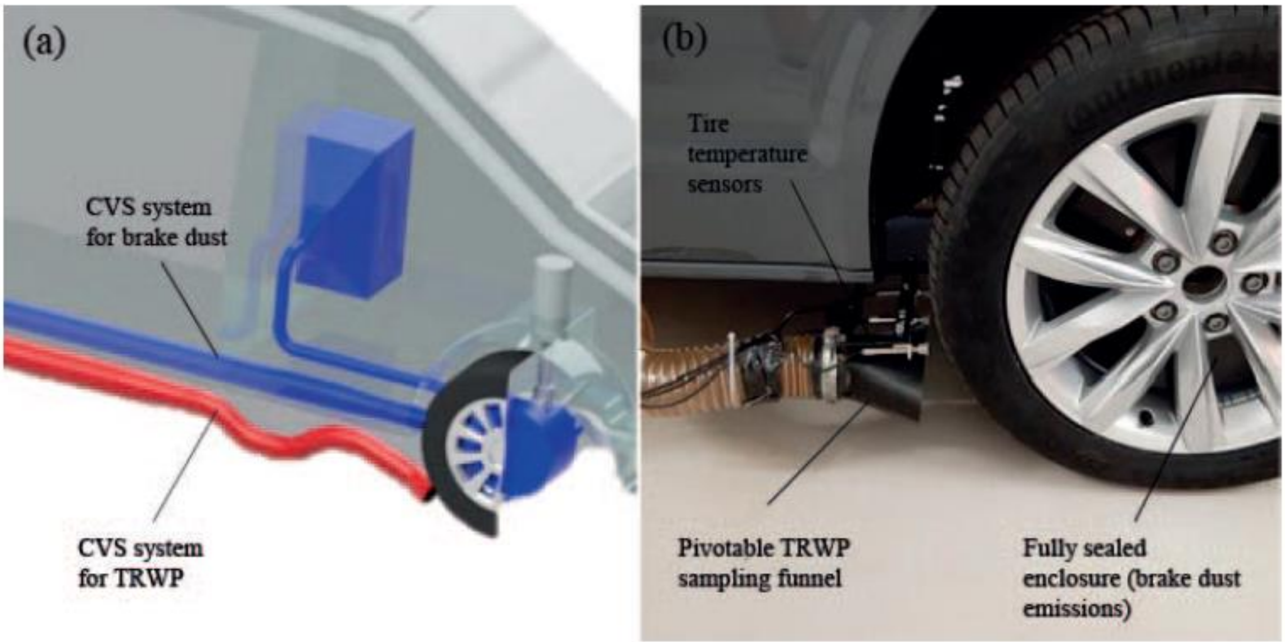


Figure 26: Vehicle-based TRWP Measurement Setup [6]

In this example, the TRWP emissions are sampled by a Constant Volume Sampling (CVS) system on the near side, i.e.: on the passenger side, behind the front tyre on a FWD vehicle. The device would be positioned behind the rear tyre on a RWD vehicle. It could also be fitted on the offside, i.e.: on the driver side, as the near side would be more likely to be contaminated with external pollution (vegetation, minerals, etc) from the roadside [4].

The brakes are fully enclosed, here, to collect the brake wear emission. This would also be a solution to avoid mixing brake wear particles at the same time as TRWP even when no brake wear emission measurement is done [6].

The TRWP sampling funnel was developed using Computational Fluid Dynamics (CFD) to identify the best position for the collecting system on the vehicle and to optimise the inlet nozzles design to maximise the sampling and transport efficiency. This means that the sampling device and installation needs to be vehicle specific. The sampling efficiency variation with vehicle speed needs to be specifically considered [4] [6].

The particle counter specifications and installation ensure an isokinetic sampling of the particles, representative of the totality of the particles collected [4] [6].

Vehicle data such as vehicle positioning, lateral and longitudinal accelerations are recorded and a representative driving cycle is followed [4] [6].

It was observed that the reliability of the TRWP emission measurement during open road testing was compromised by the influence of particles from external sources: background particles and tyre-induced resuspension. Chemical analyses using tracers such as Zn, S or SBR (for passenger car tyres) should be carried out to better determine the proportion of TRWP in the collected samples [6] [8] [10] [17].

7.3.2 VEHICLE CLOSED TRACK TESTING

The same vehicle measurement setup described for open road testing can be used for closed track testing along with the same driving cycle representative of normal driving conditions [6].

Testing on closed track compared to open road can help reduce the influence of the external sources of particles, especially if some measures are taken like closing the circuit to only allow the test vehicle on track and sweeping the circuit before each test to reduce the amount of tyre-induced particle resuspension [4].

In these conditions, testing on closed track shows a correlation with TRWP concentration and driving severity [4] [6].

To be able to better differentiate between TRWP generated during normal driving conditions and background particle concentration, an additional sampling system can be fitted under the front of the vehicle to measure background particles concentration [2].

7.3.3 LABORATORY TESTING

Laboratory testing can allow for reproducible measurements of TRWP emission.

The ISO/TS 22638:2018 standard, Rubber — Generation and collection of tyre and road wear particles (TRWP) — Road simulator laboratory method, specifies the method for generating TRWP in a road simulator laboratory representative of actual driving conditions.

Different type of systems can be considered [3]:

- Internal drum test bench: a wheel and tyre assembly is driven around the inside of large cylinder the surface of which is made of roadway material (see German Federal Highway Research Institute (BASt) setup),
- Circular road simulator: a wheel and tyre assembly is driven around a flat circular roadway surface (see Swedish National Road and Transport Research Institute (VTI) setup).

A single roller test bench, where a wheel and tyre assembly is driven on the outside of a large textured drum, can also be considered [9]. Figure 27 overleaf shows a TRWP measurement setup using this type of drum and allowing for PM10 and PM2.5 analysis.

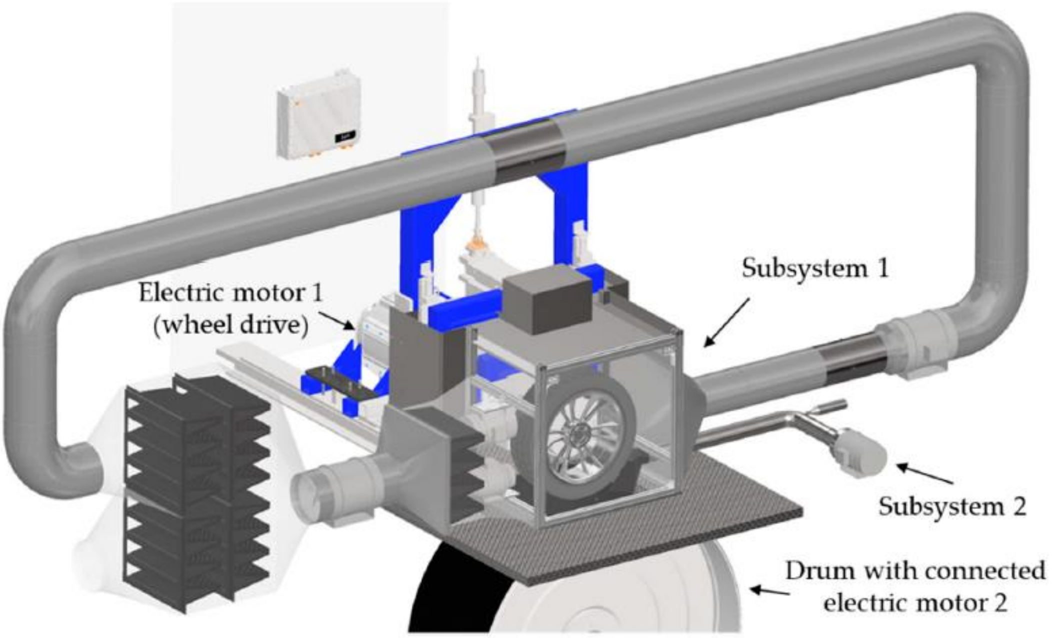


Figure 27: Single Roller Test Bench TRWP Measurement Setup [9]

The challenges when designing a test bench to measure TRWP in a laboratory are:

- Realistic forces and slip ratios simulation,
- Cooling conditions,
- Road surface characteristic.

7.4 TRWP SIZE DISTRIBUTION

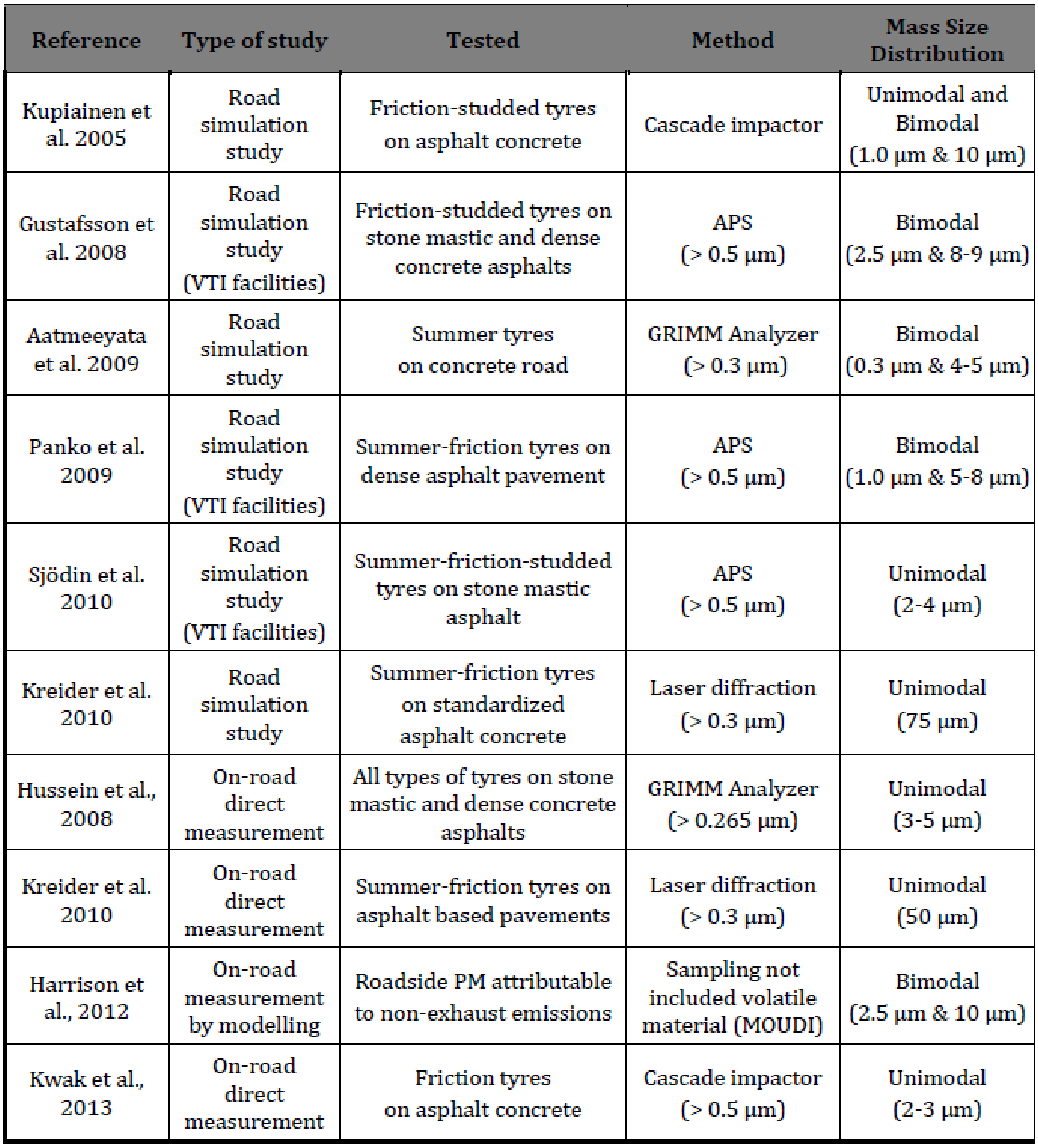
PM can be measured in terms of either mass (µg/m3) or number (number of particles/cm3). PM mass concentration is dominated by primary coarse particles (diameters larger than 1 µm) while particle number concentration is dominated by particles smaller than 1 µm and more specifically by ultrafine particles (diameter less than 0.1 µm) [15].

TRWP cover the whole range of particle sizes, from a few nm to several hundreds of µm [4] [10] [11].

7.4.1 TRWP MASS SIZE DISTRIBUTION

The TRWP median size, in terms of mass distribution, is in the 70 – 100 µm [4]. The mass distribution is highly influenced by larger particles, however, the focus of most of the studies published on the subject is on smaller particles, ie: PM2.5 and M10, the most problematic ones from an environmental point of view [10].

According to a review of studies published between 2005 and 2013, as shown in Figure 28 overleaf, tyre wear PM10 mass size distribution was found to be bimodal with one peak within the fine mode (PM2,5) and one peak among the coarser particles (PM2,5-10).



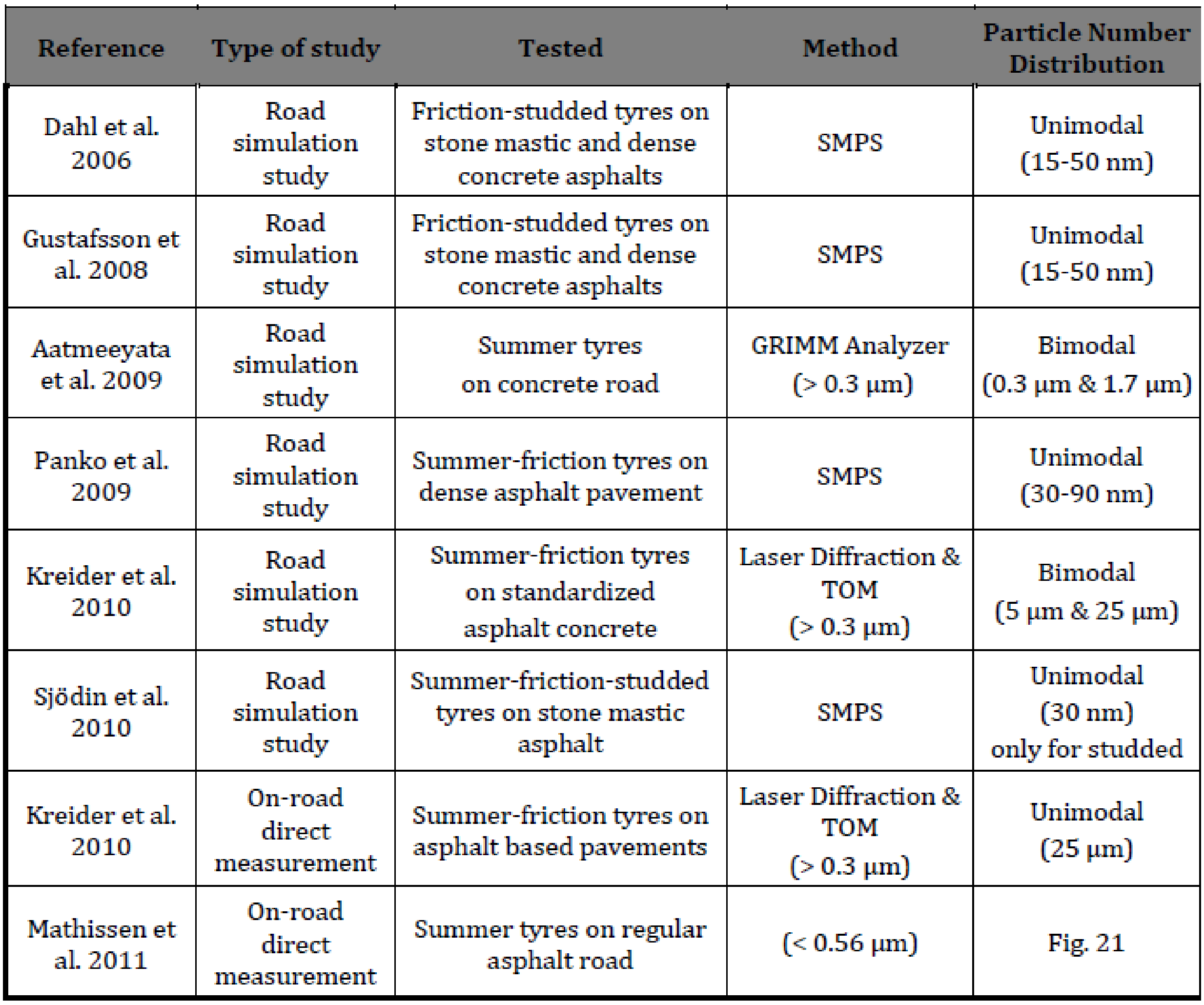
Reference	Type of study	Tested	Method	Mass Size Distribution
Kupiainen et al. 2005	Road simulation study	Friction-studded tyres on asphalt concrete	Cascade impactor	Unimodal and Bimodal (1.0 µm & 10 µm)
Gustafsson et al. 2008	Road simulation study (VTI facilities)	Friction-studded tyres on stone mastic and dense concrete asphalts	APS (> 0.5 µm)	Bimodal (2.5 µm & 8-9 µm)
Aatmeeyata et al. 2009	Road simulation study	Summer tyres on concrete road	GRIMM Analyzer (> 0.3 µm)	Bimodal (0.3 µm & 4-5 µm)
Panko et al. 2009	Road simulation study (VTI facilities)	Summer-friction tyres on dense asphalt pavement	APS (> 0.5 µm)	Bimodal (1.0 µm & 5-8 µm)
Sjödin et al. 2010	Road simulation study (VTI facilities)	Summer-friction-studded tyres on stone mastic asphalt	APS (> 0.5 µm)	Unimodal (2-4 µm)
Kreider et al. 2010	Road simulation study	Summer-friction tyres on standardized asphalt concrete	Laser diffraction (> 0.3 µm)	Unimodal (75 µm)
Hussein et al., 2008	On-road direct measurement	All types of tyres on stone mastic and dense concrete asphalts	GRIMM Analyzer (> 0.265 µm)	Unimodal (3-5 µm)
Kreider et al. 2010	On-road direct measurement	Summer-friction tyres on asphalt based pavements	Laser diffraction (> 0.3 µm)	Unimodal (50 µm)
Harrison et al., 2012	On-road measurement by modelling	Roadside PM attributable to non-exhaust emissions	Sampling not included volatile material (MOUDI)	Bimodal (2.5 µm & 10 µm)
Kwak et al., 2013	On-road direct measurement	Friction tyres on asphalt concrete	Cascade impactor (> 0.5 µm)	Unimodal (2-3 µm)

Figure 28: Literature Review – TRWP Mass Size Distribution [8]

The differences observed between the different studies results are assumed to be due to differences in experimental setup in terms of particles generation conditions, sampling and size analysis method [10] [11].

7.4.2 TRWP PARTICLE NUMBER (PN) SIZE DISTRIBUTION

According to a review of studies published between 2006 and 2011, as shown in Figure 29 overleaf, tyre wear PM10 particle number size distribution was found to be mainly unimodal but without a consensus on the peak location.

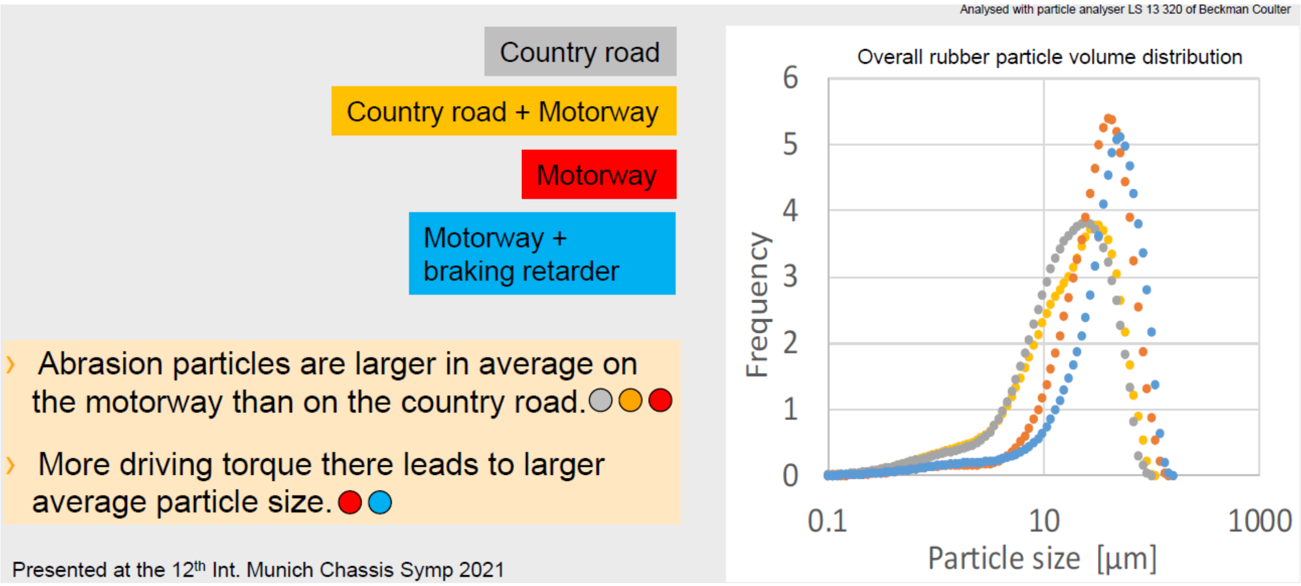


Reference	Type of study	Tested	Method	Particle Number Distribution
Dahl et al. 2006	Road simulation study	Friction-studded tyres on stone mastic and dense concrete asphalts	SMPS	Unimodal (15-50 nm)
Gustafsson et al. 2008	Road simulation study	Friction-studded tyres on stone mastic and dense concrete asphalts	SMPS	Unimodal (15-50 nm)
Aatmeeyata et al. 2009	Road simulation study	Summer tyres on concrete road	GRIMM Analyzer (> 0.3 µm)	Bimodal (0.3 µm & 1.7 µm)
Panko et al. 2009	Road simulation study	Summer-friction tyres on dense asphalt pavement	SMPS	Unimodal (30-90 nm)
Kreider et al. 2010	Road simulation study	Summer-friction tyres on standardized asphalt concrete	Laser Diffraction & TOM (> 0.3 µm)	Bimodal (5 µm & 25 µm)
Sjödin et al. 2010	Road simulation study	Summer-friction-studded tyres on stone mastic asphalt	SMPS	Unimodal (30 nm) only for studded
Kreider et al. 2010	On-road direct measurement	Summer-friction tyres on asphalt based pavements	Laser Diffraction & TOM (> 0.3 µm)	Unimodal (25 µm)
Mathissen et al. 2011	On-road direct measurement	Summer tyres on regular asphalt road	(< 0.56 µm)	Fig. 21

Figure 29: Literature Review – TRWP Particle Number Size Distribution [8]

7.4.3 TRWP SIZE DISTRIBUTION VS DRIVING SEVERITY

Several studies have shown that increasing driving severity leads to an increase in TRWP concentration [2] [4] [6] [14] [16]. Increased lateral and longitudinal accelerations as seen when driving on country roads compared to motorway generates larger average particle size, as shown in Figure 30 overleaf.



Analysed with particle analyser LS 13 320 of Beckman Coulter

Country road

Country road + Motorway

Motorway

Motorway + braking retarder

- Abrasion particles are larger in average on the motorway than on the country road. ●●●
- More driving torque there leads to larger average particle size. ●●

Presented at the 12th Int. Munich Chassis Symp 2021

Figure 30: Driving Severity influence on TRWP size distribution [17]

Driving severity increases particularly the share of PM2.5 and ultrafine particles, as shown in Figure 31 below. The assumption is that the different TRWP sizes generated depends on different wear mechanisms.

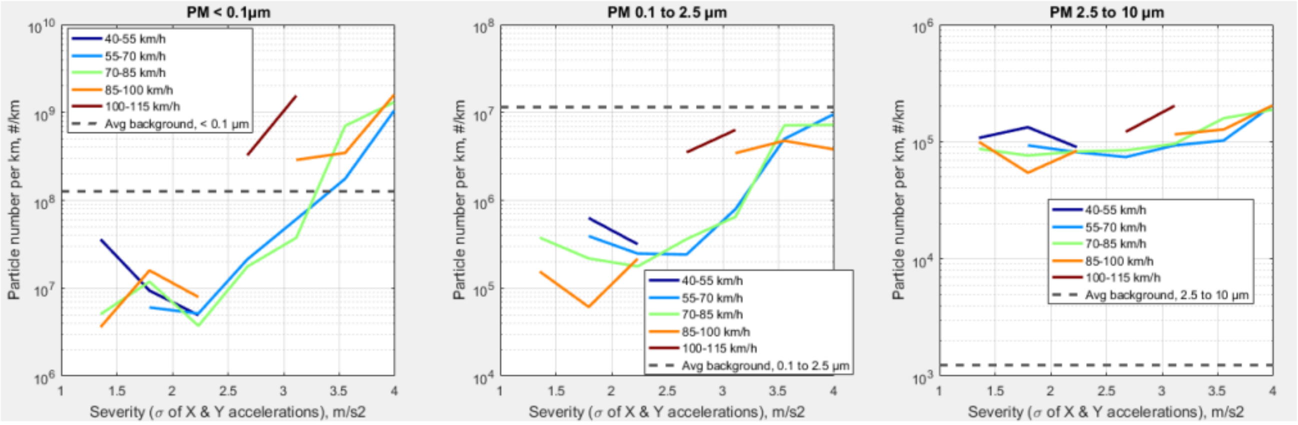


Figure 31: Driving Severity influence on TRWP size distribution (PM2.5 and PM0.1) [2]

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8. CONCLUSION

The main influencing parameters with regards to tyre wear /abrasion have been reviewed in terms of:
- Vehicle design, with a focus on the specific case of Electric Vehicles,
- Driving conditions: longitudinal and lateral accelerations were shown to be more critical than speed,
- Road surface,
- Ambient weather conditions.

From a tyre performances interdependency point of view, depending on the strategy chosen during tyre development and the category of tyre considered (designed for EVs / OE homologated vs high performance / sport), a good level of tyre wear / abrasion performance can be associated with a good level of rolling resistance and rolling noise. However, combining high levels of tyre wear / abrasion resistance and grip / handling performances can be more challenging and require investments in the development and implementation of innovative technical solutions.

When testing to determine tyre wear / abrasion rate or TRWP Emission Factor and size distribution, it is critical to use representative driving conditions since it is identified as the most influential parameter in any case.

Although the scope of the study was C1, C2 and C3 tyres, most of the documents found and reviewed were about C1 and or C2 tyres. Information about C3 tyres were included when available but currently remain limited.