



**Recommendation no. 26**

# **SUSPENSION TESTING IN VEHICLE INSPECTION**

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# 1 INTRODUCTION

CITA Recommendation no. 1 lists the items that should be inspected during periodic technical inspection of the vehicle, the method of inspection and the principal reasons for failure. Section 5 of CITA Rec. 1 covers axles, wheels, tyres, and suspension.

The purpose of this CITA Recommendation no. 26 is to specify in greater detail the recommended test methods and equipment for assessing the condition and performance of the vehicle's suspension as part of the periodic technical inspection.

A general assumption of periodic inspection is that new vehicles comply with legal requirements. The principal aim of periodic inspection is to test whether a vehicle has been properly maintained and is still roadworthy.

This CITA Recommendation is based on the requirements for suspensions stated in European Union council directive no. 2014/45/EU<sup>1</sup> on roadworthiness tests for motor vehicles and their trailers. It has been developed by the CITA Suspension Task Force.

Note: UN Rule 2 to the 1997 Agreement on uniform provisions for periodical technical inspections of wheeled vehicles with regard to their roadworthiness contains the same measures. To keep it simple, only the term "2014/45/EU" has been used throughout this document.

This CITA Recommendation describes 3 stages:

- **Stage I:** Describes suspension testing in accordance with the current EU directive 2014/45/EU.
- **Stage II:** Describes the advanced current or near-future technology. Stage II describes what can be done in addition to Stage I.
- **Stage III:** Description of possible future tests. Stage III describes what can be done besides stages I and II.

Note that some test methods are not mandatory within the European Roadworthiness Package but are best practices of CITA members who conduct these tests.

Vehicles in traffic must fulfil certain requirements that are stipulated by the legal authorities. This CITA Recommendation does not include those criteria.

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<sup>1</sup> EU Parliament and or Council directive 2014/45/EU of 3 April 2014, OJ L127 of 29.4.2014

## 2 DEFINITIONS AND ABBREVIATIONS

### 2.1 - Definitions

<b>Damping ratio</b>	The damping ratio is the proportion of the system damping coefficient to its critical damping coefficient. The system is said to be critically damped if the damping ratio prevents overshoot. Passenger cars usually have an effective mean damping ratio of around 0.3. This value gives less vehicle control but greater vehicle comfort.
<b>Adhesion (or EUSAMA value EUS<sub>i,j</sub> [%])</b>	In the context of this EUSAMA suspension test, the adhesion is the minimum percentage of residual vertical tyre contact force between the tyre and the vibrating plate during vertical oscillation of the wheel. This percentage is obtained by calculating the ratio of the minimum residual vertical load to the static weight (vertical tyre contact force) on the suspension tester. The subscripts define the wheel, where i stands for the tested axle (1, 2, etc. where 1 is the front axle) and j for the vehicle side (l = left and r = right);  $\text{Adhesion (EUSAMA VALUE) [\%]} = \frac{(N_{i,j} \text{ dyn. min.})}{(N_{i,j} \text{ static})} * 100\%$
<b>The minimum adhesion</b>	The minimum adhesion is the lowest value of adhesion throughout the test.
<b>The sprung mass</b>	The sprung mass is all mass supported by the suspension system, including parts of the suspension members. The sprung mass comprises the mass of the vehicle frame, body, and load.
<b>The unsprung mass</b>	The unsprung mass is the mass of the wheel and components that are supported directly by the wheel and considered to move with the wheel, but not carried by the suspension system. These components include mostly the wheels, tyres, brakes, parts of the axle, suspension links, suspension springs, dampers and other associated suspension components.
<b>The phase shift <math>\phi</math></b>	The phase shift $\phi$ [in degrees] is the angular difference between the absolute “sinusoidal” position of the suspension tester platform and the “sinusoidal” vertical tyre contact force between the tyre and the suspension tester platform.
<b>Artificial Intelligence</b>	A field of computer science that aims to create intelligent systems that can perform tasks that typically require human-level intelligence, such as perception, reasoning, learning and decision-making.
<b>Machine Learning</b>	Machine Learning is one aspect of Artificial Intelligence, with the overriding goal of automating tasks. It generates knowledge based on experience, generalises it and applies it to specific tasks. A machine learning algorithm learns and recognises patterns and structures in existing examples. This can then be used to make predictions for new and unseen examples by comparing the patterns found with each other.
<b>Data pool</b>	A collection of data that is stored and managed for a specific purpose, such as training machine learning models or conducting data analysis.

### 2.2 - Abbreviations

<b>AI</b>	Artificial Intelligence
<b>EUSAMA</b>	European Shock Absorber Manufacturers Association
<b>ML</b>	Machine Learning
<b>OBD</b>	On-Board Diagnostics
<b>PTI</b>	Periodic Technical Inspection

### 3 SCOPE OF INSPECTIONS

The suspension system plays a critical role in road safety, affecting for example the handling and braking distance of the vehicle. It is therefore a crucial part of the PTI. Most EUSAMA members have so far been concerned about trying to address the repeatability of the suspension testing process and the measurement. This has led to differing standards of equipment, method of use, facilities and measuring tolerances.

At this point in time, it is not mandatory to use any device to check the suspension during PTI according to directive 2014/45/EU. The directive also does not require the use of a device for lifting a vehicle on one of the axles during inspection of light vehicles. This has led to a situation where there is a lot of variation between different countries in how suspension testing is carried out during PTI. It would be beneficial in the sense of road safety to have appropriate and to some extent uniform measures for checking suspension during PTI.

Visual assessment plays an important role in suspension testing during PTI but is proving increasingly difficult in terms of finding out the state of a shock absorber's damping capability. From the PTI perspective, the recommendation should consider the cost-effectiveness of the test, the time needed to carry out the test and the benefits gained from the test. In other words, the test should be sufficiently good to ensure an appropriate level of road safety.

In this recommendation, the device testing part is recommended for the situation where new devices are being purchased. Devices that are already in use are assumed to be adequate for their purpose but should be replaced with the types described in this recommendation when they are replaced in due course.

Because of the differences in the level of testing environments (device type if any, wheel play detectors if any, axle lift device or none at all), and different testing schemes for different suspension components installed in the vehicle and/or different national requirements (e.g. different criteria for measured or assumed values), this document has been divided into three stages:

- Stage I** Describes the present minimum practice, in accordance with the current EU directive 2014/45/EU, for manual/visual suspension testing. It contains the basic points deemed important for determining the adequate working order of the suspension. The use of a suspension testing device is not mandatory, and using a wheel play detector or axle lift device is also not mandatory for light-duty vehicles.
- Stage II** Describes the current best practices of advanced or near-future technology for inspecting the working order of the suspension components of the vehicle. It also recommends other more specific conditions under which the test should be performed to get a higher level of accuracy of the results, consistency, and repeatability of the process
- Stage III** Description of future/further tests, also including other points besides testing the condition of the damping. This will be important for work in the near future.

Attached to this recommendation you will find the report.

## 4 STAGE I

Describes current minimum practice, in accordance with the current EU directive 2014/45/EU, for manual/visual suspension testing. It contains the basic points considered important for determining the adequate working order of the suspension. The use of a suspension testing device is not mandatory. For light-duty vehicles, using a wheel play detector and a device for lifting one of the axles is also not mandatory.

### 4.1 Legal requirements

See EU directive 2014/45/EU regarding suspension testing.

### 4.2 - Current situation

The suspension test actions vary across the EU from a quick and simple basic inspection up to high-effort testing like in Belgium (GOCA Vlaanderen), Finland or Germany (mandatory at TÜV-Nord, optional in other areas)

### 4.3 - Testing facility

National authorities should establish criteria for the relevant components of a suspension testing scheme, in relation to the national requirements for suspension testing for vehicles. Useful criteria should focus on relevant matters concerning the determination of the condition of vehicle's suspension.

Criteria are needed for:

- the equipment needed to test the vehicle.
- the positioning of the testing devices (also taking into consideration the weather conditions).
- the devices themselves (working principle, calibration frequency, etc.)

### 4.4 Requirements for suspension components prior to suspension testing

#### 4.4.1 Presence

A manual/visual check of the suspension components to ensure that all components are present.

#### 4.4.2 Condition

A visual check of suspension components to ensure they are in working order and for example that there are no leaks in shock absorbers, air bellows etc. This also includes a check for proper attachment and excessive wear or play in these components. It also is helpful to judge the condition of the suspension system in a short test drive (which is also recommended for the inspection of electronic safety systems).

The wear of tyres may also provide information about the condition of the suspension system (e.g. wrong wheel alignment and insufficient damping).

#### 4.4.3 Function

A manual/visual check of suspension components to ensure they are in working order by manually pressing down the corners of the vehicle and by performing a short test drive.

#### 4.4.4 Operation

The suspension components must be assembled in the vehicle in such way that the assembly fulfils the requirements given for it and the components work in the way they are supposed to.

#### 4.4.5 Compliance with requirements

The parts as assembled in the vehicle must fulfil the requirements for the vehicle.

### 4.5 Parts of the suspension that should be inspected during PTI

- Attachment and condition of springs or bellows.
- Attachment and working condition of components related to suspension: anti-roll bar (sway bar) and its fastenings, ball joints, control arms and their bushings, shock absorber mountings and bearings, wheel alignment.

### 4.6 Methods that should be used in examining the components

#### Anti-roll bar and its fastenings

Visual inspection, wheel play detector combined with visual inspection, pry-bar usage, pliers (at least for heavy vehicles). The vehicle must be lifted appropriately to ensure that there is no pressure on the joints; for some types/categories of suspension, a device needs to be used that lifts the vehicle on one of its axles.

#### Ball joints

Visual inspection, wheel play detector combined with visual inspection, pry-bar, pliers (at least heavy vehicles), correct handshake manoeuvres once the vehicle is raised in such a way that there is no pressure on the joints.

#### Control arms

Visual inspection, wheel play detector combined with visual inspection, pry-bar, correct handshake manoeuvres once the vehicle is raised in such way that there is no pressure on the joints, corrosion testing with a pry-bar and rust hammer.

#### Subframes and their attachments

Visual inspection, wheel play detector combined with visual inspection, pry-bar, corrosion testing with pry-bar and rust hammer.

#### Wheel bearings

Visual inspection, wheel play detector combined with visual inspection, pry-bar, correct handshake manoeuvres once the vehicle is raised, getting an assistant to press the brake during testing of wheel play, rotating the wheel to hear the noise of the bearing and at the same time feeling the spring for vibrations.

#### Kingpin

Visual inspection, wheel play detector combined with visual inspection, pry-bar, correct handshake manoeuvres once the vehicle is raised in such a way that there is no pressure on the pin.

#### Springs (including spring attachments)

Visual inspection, pry-bar, mirror.

#### Bellows and components that are included and connected

Visual inspection, checking for cracks, listening for leaks, pry-bar, mirror.

#### Wheel alignment

Visual inspection (severe misalignment that can be seen without tools); uneven tyre wear can be an indicator that a more thorough visual inspection is needed.

#### Strut (including spring cups etc.)

Visual inspection, pry-bar, rust hammer, mirror, turning the wheel from one end to another of the wheels steering travel while the axle is raised to check the upper strut bearing.

## 4.7 Underlying principles of the test methods used in PTI

### Visual inspection

Where a method of testing is stated as being 'visual', it means that, in addition to looking at the items concerned, the inspector will also (if appropriate) handle them, evaluate the noise they make or use any other appropriate means of inspection including the use of hand-held tools, but without dismantling components. Visual inspection does not involve using equipment.

### Wheel play detector combined with visual inspection

Should be used for all axles of vehicles to find out if there is play on steering joints, ball joints, wheel bearings and the various attachments of parts. Using a wheel play detector on the front axle is sufficient on light-duty vehicles, given that the movement of the vehicle from using the play detector is sufficient to discover defects in the rear axle suspension.

### Pry-bar usage

Pry-bar should be used to check the bushings by prying them with a bar that has enough leverage and also to check ball joints by prying them or for example lifting the tyre from beneath to see if there is too much axial play.

### Using the pliers on joints

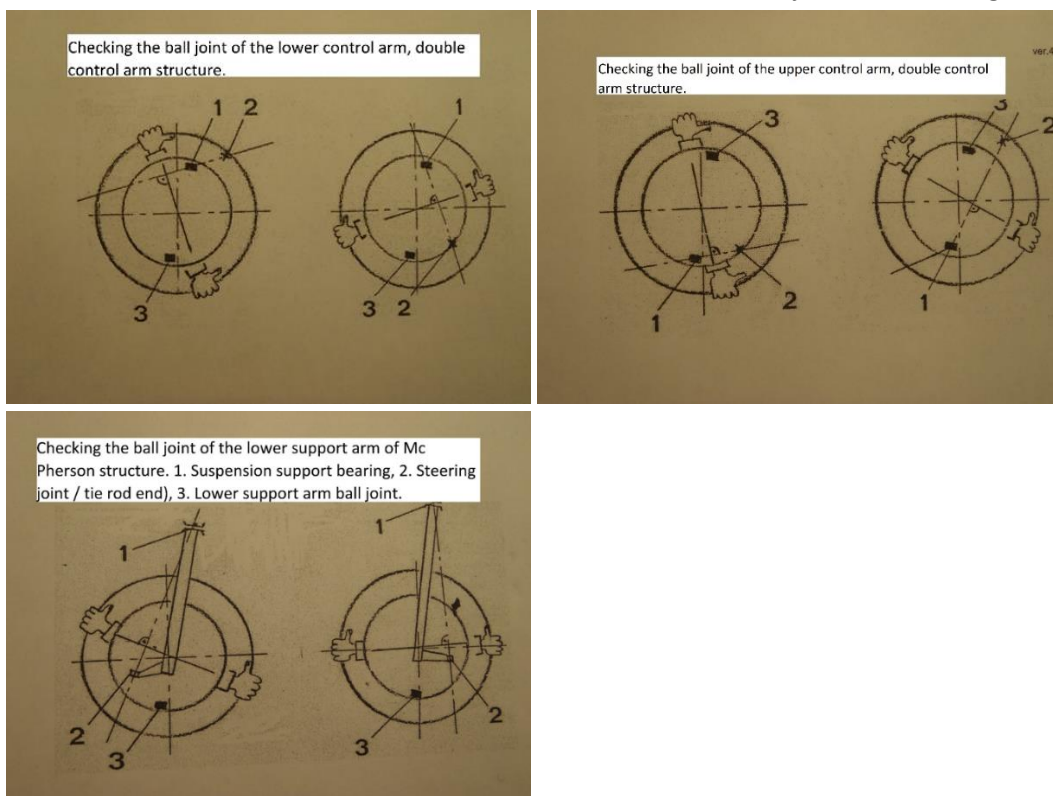
The pliers should be used for ball joints and steering joints to see if there is too much axial play.

### Raising of the vehicle axles

Using the correct raising points (and equipment and tools if the vehicle needs them)

### Correct handshake manoeuvres once the vehicle is raised in such way that there is no pressure on the joints

Manoeuvres should be such that the force is concentrated on the joint that is being tested.



## 4.8 Recommended criteria for tools used for checking suspension components in PTI

### **Flashlight**

Lighting device that can be used to check various components to help visual inspection. Can also be attached to for example remote wheel play detectors.

### **Pry-bar**

Should be about 50 – 70 cm long for light vehicles and about 1 m long for heavy vehicles.

### **Mirror**

A mirror should be used to see the springs, sub frame rust issues from the chassis or other things that are hard to evaluate merely by eye etc.

### **Pliers**

The jaw opening should be adequate for the vehicles to be inspected and always a minimum of 150 mm for heavy vehicles.

### **Axle lifting device**

The device should be such that axles can be properly lifted (enough height, from correct lifting points, enough tolerance for the mass to be lifted, correct tools for lifting from the proper points).

### **Rust hammer**

Should be such that it can be used to determine if the parts are rusted through. The length of the hammer should be about 150 mm, it should have a sharp enough end and there should be heavy enough that it can be used for knocking off the loose rust from for example control arms or struts.

## 5 STAGE II

Describes advanced current or near-future technology for checking the working order of the suspension components of the vehicle and recommends other more specific conditions under which the test should be performed to get a higher level of accuracy of the results, consistency, and repeatability of the process.

- The goal is to raise the road safety level.
- On top of the basic visual inspection, CITA recommends a mandatory, measurement-based suspension evaluation.
- Descriptions of measurement-based suspension test technologies differentiate between static (the vehicle stands still) and dynamic tests (vehicle is driving) with examples.

### Regarding the structure of the following pages

The first section of Stage II describes general requirements that are independent of the technical solution. The subsequent main section describes theoretical approaches and the distinction between static and dynamic testing. Static and dynamic suspension tests and the approaches to them, technical solutions and related requirements are the content of the later sections.

### 5.1 General requirements, independent of the technical solution

- Evaluation/assessment of the damping capability.
- Requirements for shock absorber testing (theoretical e.g. damping speed, damping force, amplitude) based on real driving conditions.
- To check dampers, it is required that the damper moves as intended and designed in terms of:
  - distance (amplitude)
  - velocity (speed)
  - force

Requirements on suspension components prior to suspension testing are the same as in Stage I (Section 4 in this recommendation). Suspension testing should be carried out in a facility that ensures that weather conditions do not influence the results of the test.

#### 5.1.1 Requirements on tested vehicle prior to suspension test

Besides the requirements stated in Stage I, the following items are recommended to be considered in Stage II prior to the suspension test.

#### Loading conditions

Loading affects the test results of the suspension test, and it is therefore recommended that the vehicle should be tested unloaded.

#### Tyre pressure

The tyre pressure affects the suspension test results; specifically, the difference between the front and rear axles. It is therefore necessary that the tyre pressure is as the vehicle manufacturer recommends.

#### Position of the vehicle

The wheels must be pointing straight ahead.

#### Position of the wheels on the test plates

The wheels must be in the middle of the test plates (static tests only).

#### Parking/service brake

The parking or service brake position could affect the measurement of the suspension. The brakes must be disengaged during testing.

## Vehicle

The vehicle must be presented in conditions defined by national authorities for the test.

Attachment of shock absorbers must be in good working order to get reliable results for the damping capability of the shock absorbers.

Criteria are for example needed for:

- Tyre pressures of the vehicle.
- Load of the vehicle.

## Alignment of vehicle

The vehicle must be correctly aligned according to the manufacturer's specifications. For example, it is required that the vehicle is driven as straight as possible on the tester platform or that the vehicle is driven at right angles over a speed bump.

### 5.1.2 User manual/training for suspension test device

It is recommended to have a proper description of the test method or a manual for the measurement device. Application videos or other training materials such as virtual training courses are also helpful.

- The suspension testing device must have a manual or training materials in the local language.
- It is advisable/necessary to follow training from the manufacturer of the device.

Sufficient theoretical and practical training is mandatory (included in the inspector's initial training).

### 5.1.3 Type approval

It is recommended to have a national authority do tests for type approval of the method in combination with the measurement device regarding:

- effectiveness at detecting worn suspension,
- suitability for use during a PTI,
- type approval procedure,
- type approval criteria.

### 5.1.4 Legal requirements

In this Stage II, it is recommended to focus not only on the recommendations from Stage I but also on:

- Evaluation of the absolute criteria for the measured values.
- Evaluation of relative criteria for the difference on same axle of the vehicle. Relative criteria are based on comparing the set of results for the left and right wheels for each axle of a vehicle, i.e. imbalance of the results for any single axle. It is obviously intended that the same level of suspension should apply for the wheels of any given axle of a vehicle. Significant differences will point to a defect in the system.
- Other required values/limits.

National authorities can prescribe their own limits/standards for assessment of all the items they require to be checked during the inspection of suspension where applicable and which vehicles will be tested with a test device.

## 5.1.5 Calibration and intervals

### 5.1.5.1 Calibration requirements

The equipment for testing suspension should be subject to calibration procedures and meet the limits given by national legislation.

### 5.1.5.2 Periodicity and frequency of calibration

Calibration should be done every two years or according to the manufacturer's specification by a qualified service person.

- The measurement devices used must be calibrated.
- The calibration interval should be defined by the local authority, taking the following points into account:
  - Accuracy
  - Long-term precision
  - Uncertainty
  - Deviation of further calibrations  
(Note: it can be recommended that the calibration interval is dynamic. If there are very few deviations, the interval may become longer – or the other way around)
  - Deviation of the device population

In accordance with the directive 2014/45/EU, it is recommended to use an initial periodicity of 2 years for the suspension testing equipment, followed by dynamic intervals.

## 5.1.6 Evaluation/assessment of the suspension system

The test should take into consideration the differences in chassis design, which affects the results.

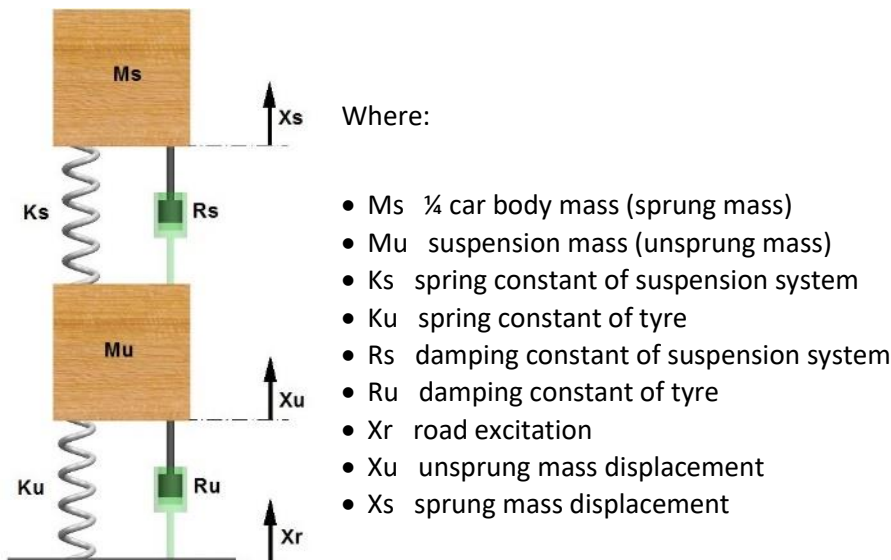
Reason for failure:

- Suspension damping capability not within limits or too much difference in the damping ratios within the same axle.
- Where an electronic vehicle interface is part of the PTI, it must not indicate a fault with the suspension system.

## 5.2 Theoretical approaches

### 5.2.1 Quarter vehicle model

When the suspension system of a car is analysed, a 1/4 model (i.e. one of the four wheels) is used to simplify the problem to a 1-D multiple spring-damper system. A diagram of this system is shown below.



From the picture above and Newton's second law, the following dynamic equations can be obtained:

$$M_s \ddot{X}_s = -R_s(\dot{X}_s - \dot{X}_u) - K_s(X_s - X_u) \quad (1)$$

$$M_u \ddot{X}_u = R_s(\dot{X}_s - \dot{X}_u) + K_s(X_s - X_u) + R_u(\dot{X}_r - \dot{X}_u) + K_u(X_r - X_u) \quad (2)$$

Where:

- $\dot{X}_r$  speed of road excitation
- $\dot{X}_u$  speed of tyre
- $\dot{X}_s$  speed of sprung mass
- $\ddot{X}_u$  acceleration of unsprung mass
- $\ddot{X}_s$  acceleration of sprung mass

These are two coupled second-order ordinary differential equations.

It is possible to determine the dynamic behaviour of the system simply by solving this system of differential equations in order to simulate how the tyre and the body will move depending on the parameters of the system and the excitation, or to compare it with measured and calculated values.

Possible excitation:

- Periodic: excitation of the plates the vehicle is standing on or driving over more than one obstacle in a well-defined distance: detect/measure the movement.
- Impulse: excitation of the plates the vehicle is standing on or driving over a ramp or a single obstacle that makes the car start oscillating detect/measure the movement.
- Stochastic: excitation of the plates the vehicle is standing on or driving over a specific or unspecified surface.

Suspension damping is determined by measuring, evaluating, and analysing the parameters given by the theoretical model or by evaluating the resulting vehicle oscillation using ML methods. The system of differential equations can be considered from two different approaches. Depending on how the vibration system is excited, there are different approaches to solving the damping dimension and thus the desired value of the damping constant of the vibration damper.

Where:

- $D_u$  damping ratio of the unsprung mass
- $D_s$  damping ratio of the sprung mass

Case one:

The excitation is via the road surface via the tyres, e.g. in a test, the chassis is simplified to being ‘sky-hooked’ (i.e.  $X_s$  equals zero), so

$$D_u = \frac{R_s + R_u}{2M_u \sqrt{\frac{K_s + K_u}{M_u}}} = \frac{R_s + R_u}{2\sqrt{M_u(K_s + K_u)}}$$

Case two:

The excitation takes place via the build-up oscillation, e.g. by impulse excitation. In this case, for the chassis oscillation after impulse, the tyre is ground-hooked and so it is possible to simplify and make  $X_r$  and  $X_u$  equal, as the tyre stiffness is about 10x higher than the body stiffness. Therefore:

$$D_s = \frac{R_s}{2\sqrt{K_s M_s}}$$

In both cases, the damping constant of the suspension system  $R_s$  is a possible desired variable for the evaluation of the suspension damping.

An example of how the theoretical approach is used for a simulated case can be found in Annex 2.

### 5.2.2 Curve fitting

The evaluation is based on a fitting algorithm that fits the measured vehicle motion to a theoretically calculated curve based on a vehicle model. The distance of the theoretical curve from the measured curve can be determined, for example by the least squares method.

The model parameters determined this way are used to calculate the damping constant. This damping constant is used as a value for assessing the condition of the suspension.

### 5.2.3 Machine Learning

In Machine Learning (ML) techniques, an algorithm “learns” from training data to derive predictions for unseen data. The implemented evaluation algorithm of the inspection technology is based on ML methods and is trained, tested and optimised on a large amount of speed bump crossings with known states of the axle damping stored in the data pool.

The data pool, which is essential for ML, is the starting point and mainly consists of the measured acceleration and rotation rate signals of the recorded speed bump crossings. This data pool is created with field vehicles of different models, with guaranteed intact or defective axle damping. This allows numerous variations in vehicle age, type, equipment, wheels, and tyres to be considered.

The data pool therefore contains a representative selection of the most common vehicles, also with sporty chassis variants. The extensive size of the dataset allows it to be split into two datasets (training and test datasets), which are equally representative samplings of the vehicles in the field.

The ML training process generates a classifier that can identify general patterns of intact or deficient axle damping in the training data. The classifier produced is then tested and validated against unseen test data. Speed bump crossings of unknown, different or new vehicles not included in the data pool can also be classified correctly. To optimise the performance and robustness of the evaluation algorithm, various further vehicles are measured continuously and added to the data pool.

### 5.3 Static Suspension tests (vehicle is stationary)

#### Theoretical approaches

Static suspension test approaches are usually based on the quarter vehicle model (see Section 5.2.1.) where the chassis is 'sky-hooked'. That means that the oscillation stimulation is carried out by moving the wheels, which stand on plates, and the 'sky-hooked' vehicle chassis is static and does not move.

Depending on the implementation, related wheel forces and movements get measured and evaluated.

#### 5.3.1 Technical implementation (linked to theoretical Approaches)

The principle is to excite the unsprung mass of the vehicle at its resonant frequency. At that point, the adhesion between the suspension bench plate and the wheel is at its minimum. The resonance frequency can be determined graphically because it corresponds to the point of inflection of the curve. The bench excites the unsprung mass over a range from 0 to 25Hz.

Mechanically, the suspension bench has a motor (one per side or one for the entire system) that rotates an eccentric driver, connected to suspended plates, on which the wheels of the vehicle rest.

The EUSAMA method considers the mass of the vehicle and its fluctuation.

$$\text{EUSAMA value (\%)} = F_{\min} \div F_{\text{stat}} * 100$$

$M_{\min}$ : minimum value of the apparent wheel load on the plate during the test

$M_{\text{stat}}$ : static value of the wheel load on the plate.

The BOGE method considers the displacement of the suspension bench plate after excitation. It uses a linear extrapolation of plate displacement to estimate vehicle mass throughout the test.

THE PHASE SHIFT  $\Phi$  [in degrees] is the angular difference between the absolute 'sinusoidal' position of the suspension tester platform and the 'sinusoidal' vertical tyre contact force between the tyre and the suspension tester platform. In practice, the phase shift is calculated from the top position of the compensated force signal and the top position of the plate.

The top position of the plate will be measured directly. The top position of the compensated force signal should be calculated as the middle of the intersection of the compensated force signal and the static weight, when this intersection is available, and the static weight is somewhere in the range between max and min.

For phase shift calculation (in the range of 20Hz to 5Hz), the compensated force signal must be digitally filtered with a filter that does not change the compensated force signal phase and that removes all parasitic influences.

Minimum phase shift must be detected at a frequency that is 3Hz ( $\Delta F$ ) below the EUSAMA frequency. When the force signal goes below 0 EUSAMA (underflow), the EUSAMA frequency should be taken at the maximum upper envelope of the force signal in the area where the force signal is 0. When the force signal goes below 0 EUSAMA (underflow) and goes above the limit of the physical recording of this force signal (overflow), so that the sinus waves are cut off, this  $\Delta F$  must be taken from the first waveform where signal gets back within systems hardware range.

The minimum phase shift  $\phi_{\min}$  is the lowest value of the phase shift  $\phi$  determined during the test between the sprung and unsprung mass resonant frequencies.

The minimum phase angle value is indicative of the strength of the damping. The minimum phase angle is the lowest value of the phase angle determined during the test between the sprung and unsprung mass resonant frequencies. When adequate damping is present in the suspension system, there will be a smoother response delay of the wheel to the moving platform at the unsprung mass resonant frequency.

The platform is excited by a frequency variation (0Hz – 25Hz – 18Hz – 8Hz - 5Hz – 0Hz), according to the Frequency Variation Function, using a sinusoidal function at constant amplitude (approx. 3 mm). The frequency inverter should be of the 'vector-controlled' type (real vector control). The frequency inverter should be able to complete at least 800 entire cycles per day to guarantee long-term working without problems.

The vector-controlled frequency inverter should be programmed as follows:

The power supply and the frequency variator should be capable of driving the platform, when loaded to its maximum from rest position to its maximum frequency of about 25Hz in considerably less than 2.5 seconds. An overrun at 25Hz is allowed but should be minimised. To measure the rigidity of the tyre at 25Hz, the suspension tester will be at this frequency for 0.5 seconds after the stability of the vehicle is obtained for a minimum of 2.5 s. A fast downward linear function should be obtained from 25Hz to 18Hz in order to minimise the test duration. Further steps down from 18Hz to 5Hz with a linear pass-through of 7.5 s from 18Hz to 8Hz and continued until 5Hz. After 5Hz, the converter may break the flywheel.

A minimum phase angle of less than 40 degrees, corresponding to damping ratio of 0.08 for the unsprung mass, is considered to be weak. The absolute criterion for the minimum phase shift is therefore set to 35°. Relative criteria are based on comparing the set of results between the left and right wheels for each axle of a vehicle, e.g. imbalance of the results for any single axle. It should obviously be clear that the same level of suspension is intended for the wheels of any single axle of a vehicle. Significant differences will point to a defect in the system.

The relative criteria for the minimum phase shift are set to 50%.

### 5.3.2 Suspension testing device

#### 5.3.2.1 Equipment technology

Devices used in suspension testing can have the working principle of EUSAMA, amplitude, theta, or evaluation of the measured acceleration/amplitude and/or rotation rate of the chassis in one pass plus an evaluation using machine learning technologies. Wheel detector plates should be used together with visual inspection to determine the working order of suspension components.

### 5.3.2.2 Equipment criteria

Any suspension testing device should be capable of evaluating values for suspension characteristics per wheel for N1 and M1 vehicles. The operation of a suspension testing device should not extend the time for PTI (Periodic Technical Inspection) significantly. Testing devices must be built to good engineering standards, covering all applicable requirements for technical devices in general (e.g. directives about product safety, etc.).

The construction and functioning of test devices should be designed in a way that will not cause any damage to tested vehicles, but which is easy to operate with low maintenance costs and may be prepared for automatic data transfer.

National authorities should establish criteria for the relevant components for the suspension testing systems needed in relation to the national requirements in suspension testing for vehicles.

Requirements:

- Measure physical values such as distances, accelerations, and frequencies.
- All suspension testing devices need a type approval.
- Tolerance of the measurement.

### 5.3.3 Preconditions

Test facility, tested vehicle (tyre pressure, loading, brake and steering wheel)

EUSAMA/BOGE, phase shift: The ambient temperature should be in accordance with the equipment manufacturer's requirements. The vehicle must be positioned symmetrically on the suspension bench, each wheel in the middle of the plate, in the axis of the vehicle. The inspector should not touch the steering wheel during the test. The tyre pressure must be in accordance with the vehicle manufacturer's requirements. The vehicle must not be loaded. No brake applied (neither pedal nor handbrake).

### 5.3.4 Test procedure

The vehicle is driven on the test bench and stopped so that wheels being tested are placed in the middle of the test plates. Once the vehicle is in the right place, the test will start automatically. When the test is done the device will show the results for each tested wheel.

### 5.3.5 Evaluation of the suspension

EUSAMA/BOGE, phase shift:

It is impossible to check only the shock absorbers because all running gear components are excited by the plate (tyre, bearing, spring, etc.). We can only analyse the left/right difference between the damping ratios on the same axle.

These methods are sensitive to load, tyre pressure and tyre stiffness.

## 5.4 Dynamic Suspension tests (vehicle is MOving)

### Theoretical approaches (linked to theoretical approaches)

Dynamic suspension test approaches are usually based on the quarter vehicle model (see Subsection 5.2.1.) where the wheels are 'ground-hooked'. This means that the oscillation stimulation is carried out by moving the vehicle chassis during a test drive (e.g. over speedbump) and the wheels are 'ground-hooked' on the road and follow the road excitations. The vehicle chassis movement can be described e.g. by coupled quarter car models or full-vehicle models, which describe all three translational and three rotational degrees of freedom. Chassis movements in all six degrees of freedom can be used to evaluate suspension properties. Depending on the implementation, the related vehicle and chassis forces and movements get measured and evaluated.

### 5.4.1 Technical implementation

AI/ML methods use acceleration sensors and gyroscopic sensors to detect vehicle movement. The evaluation can be based on machine learning.

The Bosch and Beissbarth methods both use cameras to detect vehicle movement, one using a test bench, one using a speedbump. The evaluation is based on curve fitting (see 5.2.2).

The following technical implementation is described in the following subsections (for the other methods, see 6.1):

- the suspension test with the PTI-Adapter.

### 5.4.2 Testing device

The PTI adapter is a compact, robust and universal testing and deceleration measurement device for periodic technical inspection. It lets the PTI inspector both communicate with the vehicle's electronics via the electronic vehicle interface and measure the vehicle's dynamic parameters.

The PTI adapter as a measurement device contains a triaxial acceleration sensor and a triaxial angular rate sensor.

Minimum requirements:

- measurement range: acceleration min. approx. 16 m/s<sup>2</sup>, angular rate approx. 50°/s
- Sampling rate: 100Hz
- Periodic calibration

A speed bump is required to stimulate the vibration that is as wide as the usual vehicles are and with a specific height and width.

### 5.4.3 Precondition

- Enough space to drive over the speedbump (4 times a vehicle length)
- The underground should not cause additional vehicle oscillations: it should be even and level.
- The tyre pressure should be checked beforehand if visible deformations are recognisable (approx. 0.5 bar from the usual pressure guarantees reliable results)
- The vehicle is not loaded with more than an additional 50 kg.

### 5.4.4 Test procedure

- Positioning of PTI adapter in the rear foot well, behind the driver's seat, in the direction of travel
- After the test start, an automated routine aligns the car's and PTI adapter's coordinate systems regarding roll & pitch. During the alignment measurement, the car should not move: an audio signal is audible.
- Drive over a standard speed bump at about 8 km/h (1st gear, idle). This pulsed stimulation causes a defined vehicle oscillation. The PTI adapter records the resulting vehicle movement.
- Stop the measurement 3 seconds after the rear axle passes the speed bump or drive further until the timeout is reached.
- The classification of recorded data starts automatically, and the evaluation result is displayed.

### 5.4.5 Evaluation of the suspension

The ML evaluation is based on a huge dataset of speedbump drives under predefined conditions.

## 6 STAGE III

Description of future/further tests including also other points besides testing of the damping condition. An important work for the near future.

### 6.1 Beissbarth drive-through suspension test

#### 6.1.1 Testing device (Beissbarth drive-through suspension test bench)

Depending on the technical solution.

- Speedbump wider than the vehicle
- Camera on each side observing the vehicle and wheel movement.

#### 6.1.2 Precondition

- Enough space to drive over the speedbump (4 times a vehicle length)
- The underground should not cause additional vehicle oscillations it should be even and level.
- The tyre pressure should be checked before, if visible deformations are recognisable (approx. 0.5 bar from the usual pressure)
- The vehicle is normally loaded (not more than additional 50 kg).

#### 6.1.3 Test procedure

- Start the test procedure,
- Drive over the speedbump in the test bench with a velocity of 7 km/h,
- Automatic recording of the vehicle movement,
- Stop the test procedure,
- Evaluate the condition, based on the measurement.

#### 6.1.4 Evaluation of the suspension

- The evaluation is based on a fitting algorithm, aligning the measured vehicle movement to a theoretically calculated curve based on a vehicle model. The determined model parameters are used to calculate the damping constant,
- A camera system is used for optical detection of the vehicle position and the chassis position on each vehicle side,
- Minimise the deviation between the measured chassis movement and the theoretical chassis movement using the least squares error function,
- Determine the damping constant, the spring rate and the body mass; from there, determine the damping constant.

### 6.2 Outlook – Focus on ML development

Many testing organisations have already been using the ML axle damping test as part of the general inspection since its release. The user feedback is the basis for continuous advancement and progression of the axle damping test technology. The inspector is therefore integrated into the development process by combining abnormalities with measurement data from the PTI adapter, recorded during a speed bump crossing. This linked measurement data can then be fed into further machine learning processes to refine and enhance the test technologies for the inspector and can thus make their work even easier and more efficient.

It will be possible to detect not only weak dampers, but also weak ball joints or broken springs based on the PTI test drive measurements:

- collecting measurement data during PTI test drive (mandatory in some EU Member States),
- collecting corresponding PTI inspection results,
- combining the PTI inspections results with the corresponding measurement data with ML methods,
- finding patterns of degradation in the measurement data,
- offering an additional test technology to the inspectors.

### 6.3 Further technologies

- Half power test rig
- Wheel movement observation and using curve fitting or ML:
  - Sensors
  - Camera
- Dynamic test driving the left and right wheels separately over a speedbump
- Dynamic test driving at a predefined angle over a speedbump
- Using sensors built into the vehicle combined with pattern recognition based on state vectors (patents) Intelligent Speedbump.

## 7 FINAL RECOMMENDATION AND CONCLUSION

Any usage of an additional testing method will improve the safety. National authorities should therefore be required to make it mandatory to lift the axles during PTI and implement an additional, measurement-based suspension test method (or several of them).

## 8 APPENDIX

### APPENDIX 1: UNDERLYING CRITERIA FOR THE SUSPENSION TESTING DEVICE

1. Without requiring any adjustments, the suspension tester should be capable of testing vehicles with:
  - Static wheel loads from 100 up to at least 850 kg
  - Track widths from 1000 to 1700 mm
  - Wheelbases differing from left to right by up to 100 mm on the same vehicle.
2. Without suffering any damage or adverse effects to its metrological or other qualities, the installation must be able to tolerate the loading, impacts and vibrations that are exerted or caused by the wheels on the platform during normal operation of the bench in the abovementioned loading conditions for a period of at least 5 years. The term 'normal operation' means being used for a minimum of 300 measurements (a = axles) per day.
3. Normal functioning of the equipment must be guaranteed for ambient temperatures of between -5°C and 35°C.
4. A simple selection should allow the suspension tester to be put in the automatic (normal) cycle. The operation for this selection must be easily accessible.
5. Appropriate measures need to be taken to ensure that no negative effects can arise due to condensation.
6. The suspension tester also has to be protected against normal weather conditions, corrosion and penetration of foreign (abrasive) materials into the bearings or moving parts. It also has to be protected against floor cleaning products and dirt and water (including salty water) falling from vehicles during testing.
7. The measurement mechanisms for the vertical loading must have an adjustment device that is moreover secured against arbitrary manipulation. The calibration and adjustment must be able to take place within an acceptable time frame (less than 120 minutes) and it must be easy to dismantle them when required.
8. The suspension tester must start up automatically after the vehicle is positioned and once a significant and stable static vertical force is measured.
9. The measurement devices must have the CE marking. All obligations relating to CE marking and the EU Machinery Directive are wholly the responsibility of the supplier of the suspension tester.
10. All parameters that are governed by software must be protected and it must be possible for an authorised user to adjust and secure them easily. All parameters must be retained, and it must always be possible to print out the valid settings on a dated printout.
11. For initial scale maintenance, the equipment must be easily accessible, and it must be possible to clean it easily, so that such maintenance can be carried out within a reasonable time scale.
12. The equipment must have an emergency stop function. The emergency stop function must be located in the vicinity of the suspension tester, PC or console.
13. The measurement mechanism has to comply with all conditions as laid down in European laws, regulations, guidelines and standards as valid at the time of purchase with regard to safety, hygiene, working conditions and the environment.
14. The electrical signals for the vertical forces and the vertical position of the oscillating platform measurements must be filtered to allow correct evaluation not only of these direct measurements but also of the derived quantities relating to damping capacity and imbalance. The response times of the various variables measured should be very small.

The filtering processes and the response times for the various direct measurements should always remain in step, so that not only the measurement results themselves but also the derived quantities are always based on measurements that have taken place at the same time or measurements taken within the same time interval. These filters should preferably be adjustable by setting the parameters via the software.

**15.** The devices will be protected against incorrect operation and excessive variations of the voltage supplied. The unit will have a three-phase power supply 220/380V AC 50Hz. Fluctuations of the power supply by approx. 15% will not affect the accuracy of the measurements or disrupt the automatic operation.

## APPENDIX 2: TRANSFER FUNCTION MODELS, DETAILS AND CALCULATIONS BASED ON THE 'SKYHOOK'

We will assume that all the initial conditions are zero, so that these equations represent the situation where the vehicle wheel hits a bump or other excitation. The dynamic equations above can be expressed in the form of transfer functions, using the Laplace transform. The specific derivation from the above equations to the transfer functions G1(s) and G2(s) is shown below; each transfer function has outputs of Xu and Xs, and inputs of Xr.

$$(M_s S^2 + R_s S + K_s) X_s(S) - (R_s S + K_s) X_u(S) = 0 \quad (3)$$

$$(-R_s S + K_s) X_s(S) + (M_u S^2 + (R_s + R_u) S + (K_s + K_u)) X_u(S) = (R_u S + K_u) X_r(S) \quad (4)$$

Writing the equations in matrix form:

$$\begin{bmatrix} M_s S^2 + R_s S + K_s & -(R_s S + K_s) \\ -(R_s S + K_s) & M_u S^2 + (R_s + R_u) S + (K_s + K_u) \end{bmatrix} \begin{bmatrix} X_s(S) \\ X_u(S) \end{bmatrix} = \begin{bmatrix} 0 \\ (R_u S + K_u) X_r(S) \end{bmatrix} \quad (5)$$

and defining the following:

$$A = \begin{bmatrix} M_s S^2 + R_s S + K_s & -(R_s S + K_s) \\ -(R_s S + K_s) & M_u S^2 + (R_s + R_u) S + (K_s + K_u) \end{bmatrix} \quad (6)$$

and:

$$\Delta = \det \begin{bmatrix} M_s S^2 + R_s S + K_s & -(R_s S + K_s) \\ -(R_s S + K_s) & M_u S^2 + (R_s + R_u) S + (K_s + K_u) \end{bmatrix} \quad (7)$$

Then:

$$\Delta = (M_s S^2 + R_s S + K_s) \cdot (M_u S^2 + (R_s + R_u) S + (K_s + K_u)) - 2 (R_s S + K_s) \quad (8)$$

Find the inverse of matrix A and then multiply using the inputs  $X_r$  on the right-hand side as follows:

$$\begin{bmatrix} X_s(S) \\ X_u(S) \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} M_u S^2 + (R_s + R_u) S + (K_s + K_u) & -(R_s S + K_s) \\ -(R_s S + K_s) & M_s S^2 + R_s S + K_s \end{bmatrix} \begin{bmatrix} 0 \\ (R_u S + K_u) X_r(S) \end{bmatrix} \quad (9)$$

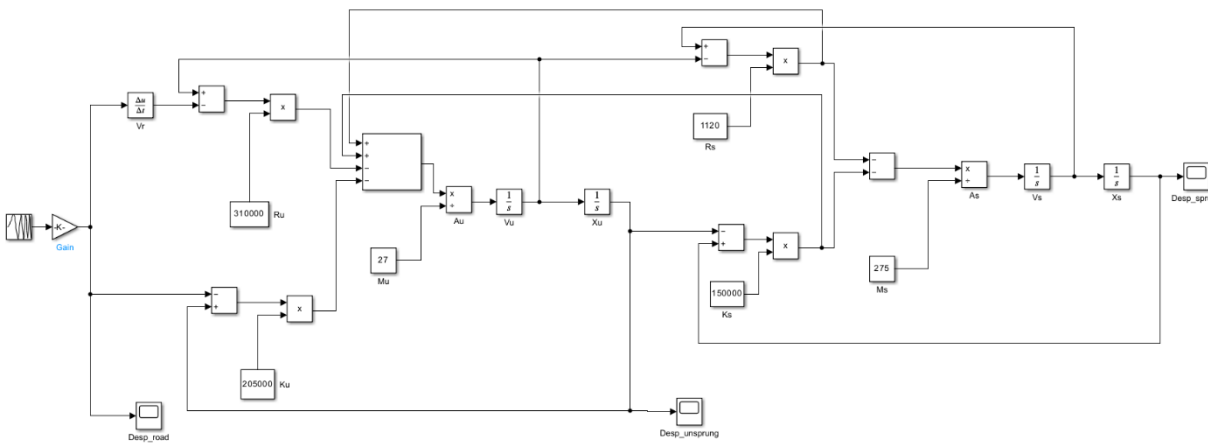
$$\begin{bmatrix} X_s(S) \\ X_u(S) \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} M_u S^2 + R_u S + K_u & -(R_s S + K_s) \\ M_u S^2 & M_s R_u S^3 + (M_s K_s + R_s R_u) S^2 + (R_s K_u + R_u K_s) S + K_s K_u \end{bmatrix} \begin{bmatrix} 0 \\ X_r(S) \end{bmatrix} \quad (10)$$

To analyse the behaviour of the system due to the disturbance input  $X_r(s)$ , the transfer function  $G(S)$  is as follows:

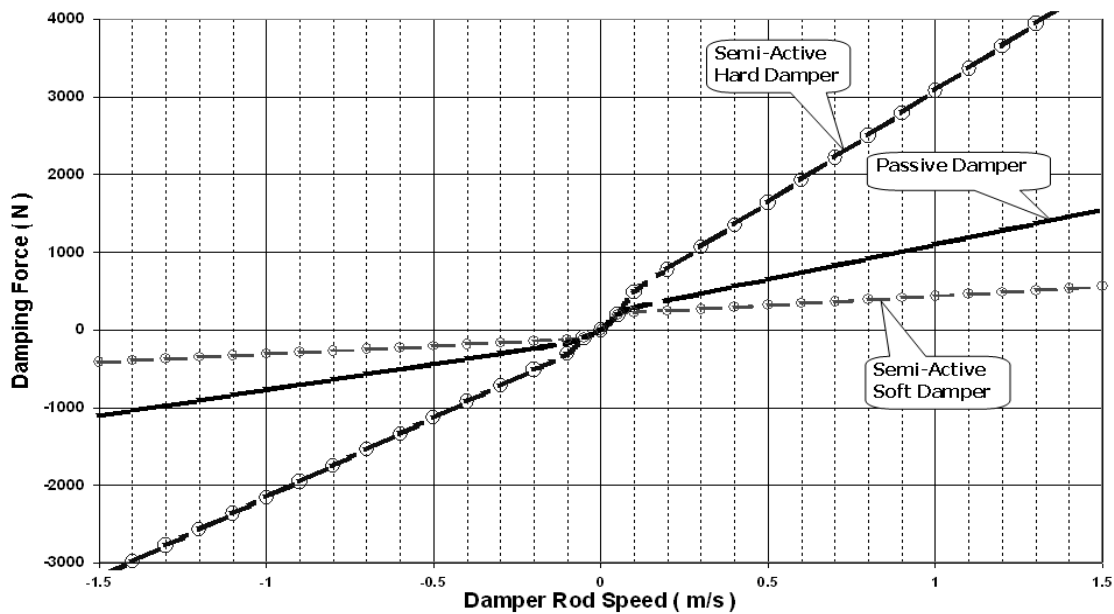
$$G(S) = \frac{X_s(S) - X_u(S)}{X_r(S)} = \frac{-M_s R_u S^3 - M_s K_u S^2}{\Delta} \quad (11)$$

It is possible generate the above transfer function models in MATLAB by entering the corresponding commands in the MATLAB command window.

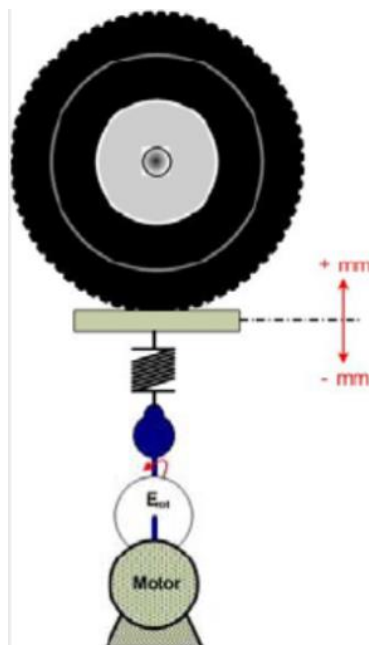
The equations can also be solved using a SIMULINK model such as the one presented below. This makes it very easy to modify the type of excitation and obtain the displacements, velocities and accelerations of the sprung and unsprung masses as the results.



The advantage of working with SIMULINK is that the real-world behaviour of the damper can be modelled simply without being limited to using constants for its behaviours, as shown in the following figure.



The model makes it possible to obtain the response of the body as well as the adhesion force between the tyre and the road for various damping values, evaluating and analysing the parameters given by the theoretical model or by evaluating the resulting vehicle oscillation. For example, for a vehicle of the C segment whose mean parameters are those shown in the table below, we can analyse the response for various damping values on a vibrating test bench.



PARAMETER	VALUE	UNITS
Ms (sprung mass)	300	Kg
Mu (unsprung mass)	30	Kg
Ks (spring constant of suspension system)	24,200	N/m
Ku (spring constant of tyre)	220,000	N/m
Rs (damping of suspension system) Optimum	1616 ( $\xi=0.3$ )	Ns/m
Rs (damping of suspension system) Worn out	270 ( $\xi=0.05$ )	Ns/m
Ru (damping constant of tyre)	100	Ns/m

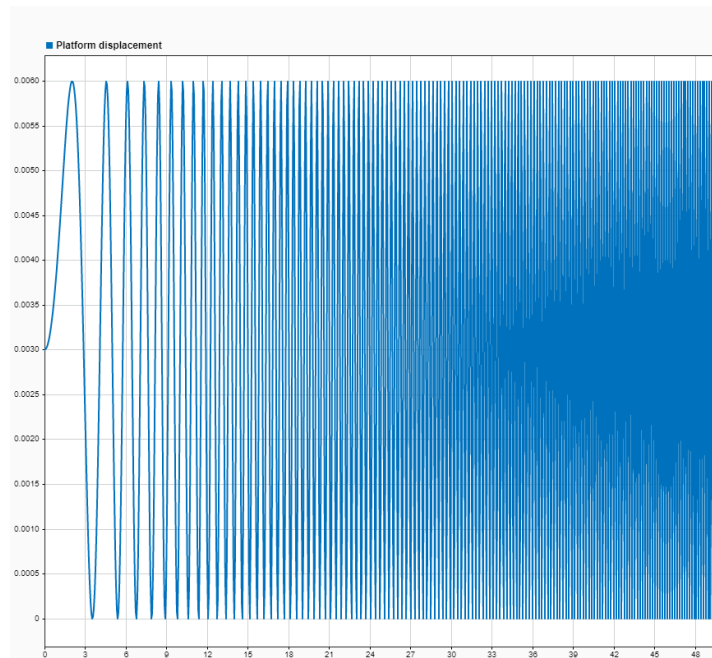


Fig. 1: Platform displacement (m)

The figures below present the results for a damper in optimum condition. ( $\xi=0.3$ )

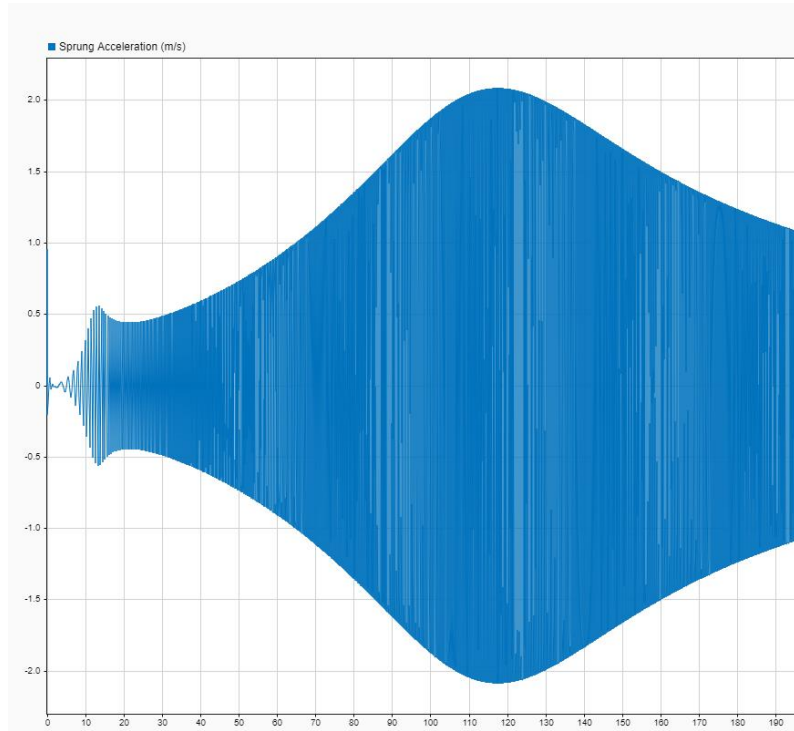


Fig. 2: Sprung mass acceleration ( $\xi=0.3$ )

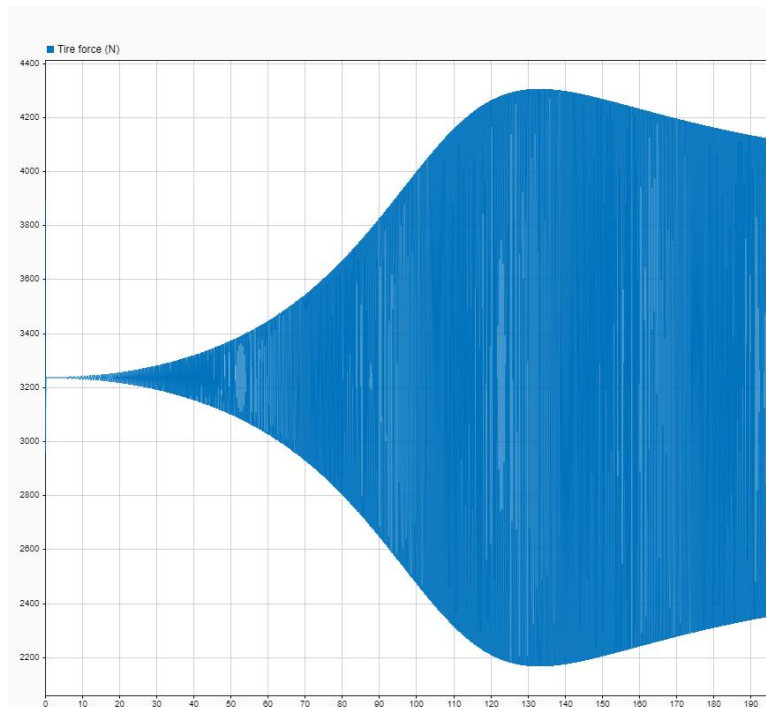


Fig. 3: Tyre force ( $\xi=0.3$ )

The figure below presents the results for a shock absorber in poor condition ( $\xi=0.05$ )

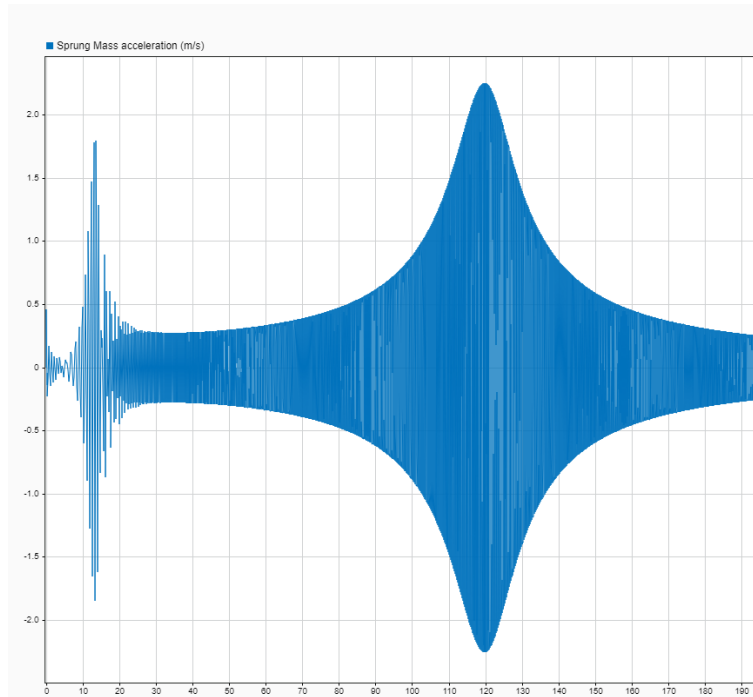


Fig. 4: Sprung mass acceleration ( $\xi=0.05$ )

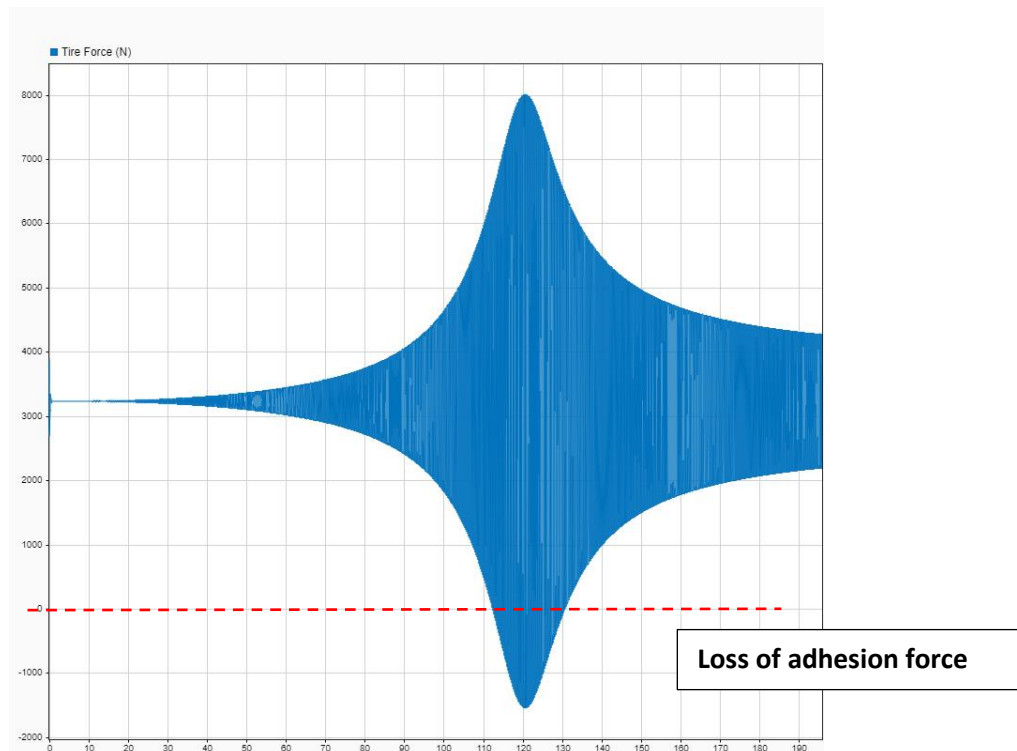


Fig. 5: Tyre force ( $\xi=0.05$ )

If the shock absorber is damaged, there is a loss of adhesion force between the tyre and the platform.