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REVIEW ARTICLE

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Ride analysis tools for passenger cars: objective and subjective evaluation techniques and correlation processes – a review

Giuseppe Guastadisegni[a,b], Stefano De Pinto[a], Daniele Cancelli[a], Stefano Labianca[a], Antonio Gonzalez[a], Patrick Gruber [b] and Aldo Sorniotti [b,c]

[a]McLaren Automotive Limited, McLaren Technology Centre, Woking, UK; [b]Department of Mechanical Engineering Sciences, University of Surrey, Guildford, UK; [c]Department of Mechanical and Aerospace Engineering, Polytechnic University of Turin, Turin, Italy

ABSTRACT
In passenger cars, the ride characteristics are fundamental to the driver and passenger engagement, as they define the comfort and road holding performance. Therefore, the methods and tools to assess ride quality are of significant interest to the vehicle dynamics specialists, and are an important part of the internal know-how of each car maker and Tier 1 supplier, which is often kept confidential. Unfortunately, the available literature does not include a comprehensive survey on the evaluation of the objective and subjective aspects related to ride, and their correlation. This review targets the gap, and deals with: (i) the available tools and techniques to objectively assess primary and secondary ride, including typical manoeuvres, road profiles, required vehicle instrumentation, and key performance indicators (KPIs); (ii) the subjective attributes and their categorisation; (iii) the approaches and mathematical models to correlate the objective KPIs with the subjective evaluation; and (iv) future trends. The know-how of the authors on the ride assessment of high-performance passenger cars will also be used to cover the aspects that are currently overlooked by the available literature and standards. In summary, the manuscript provides the interested reader with useful guidance on the procedures to perform ride quality analyses.

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Primary ride; secondary ride; objective key performance indicators; subjective attributes; measurement procedures; correlation

1. Introduction

Vehicle ride is considered a 'measurable motion environment (including vibration, shock, translational and rotational accelerations) as experienced by people in or on the vehicle' [1]. These accelerations result mainly from road irregularities, which excite the motions of the vehicle wheels, bringing vibrations that are transmitted to the driver through the steering wheel, seat, and pedals, i.e. the relevant human machine interfaces. Other excitations are caused by the powertrain, or by the driver inputs associated with steering, acceleration,

CONTACT Aldo Sorniotti a.sorniotti@surrey.ac.uk, aldo.sorniotti@polito.it

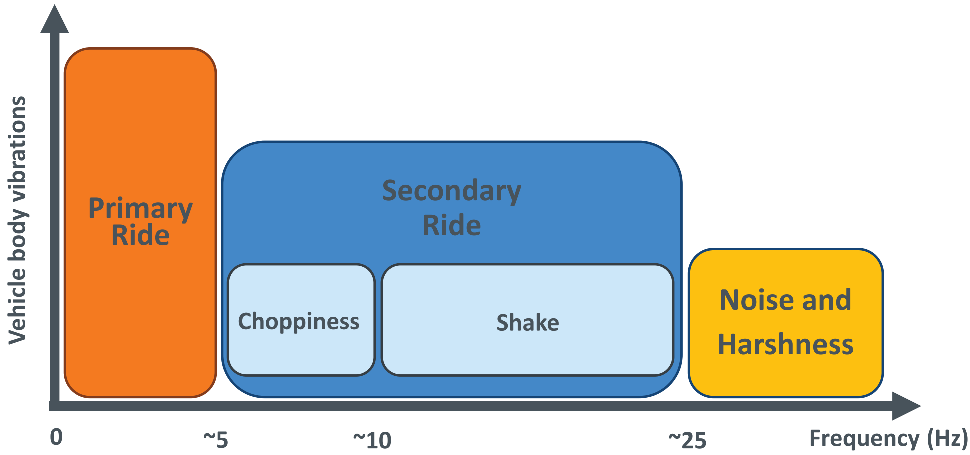


Figure 1. Graphical definition of the ride frequency ranges.

and braking [2,3]. Vehicle ride can be divided into two major categories according to the frequency range of the associated vibration, see Figure 1 [4–10]:

(1) Primary ride, which includes vibrations with a frequency range from ∼0.5 to ∼5 Hz, and is related to the heave, roll and pitch motions of the sprung mass.
(2) Secondary ride, which is associated with vibrations ranging from ∼5 to ∼25 Hz, typical of the suspension and wheel modes, which are transmitted to the sprung mass. Secondary ride vibrations are usually categorised into [3]:
   - Choppiness, with a frequency range from ∼5 to ∼10 Hz, associated with the vertical, longitudinal, and lateral accelerations of the vehicle body, giving the perception that the sprung and unsprung masses move in-phase.
   - Shake [11], with a frequency range from ∼10 to ∼25 Hz, related to vibrations mainly due to the engine or electric powertrain shake, driveline, steering column, and suspension.

The previous definitions will be used in the remainder. Nevertheless, several studies divide primary and secondary ride differently, e.g. some of them extend primary ride up to ∼10 Hz, and secondary ride up to ∼80–100 Hz [12]. Figure 1 also highlights that the amplitude of the oscillations tends to reduce with increasing frequency values.

The frequency range below 0.5 Hz tends to provoke motion sickness, namely the discomfort associated with dizziness, fatigue, and nausea [13], which is expected to become especially relevant in the next generations of highly automated vehicles [14–21]. As motion sickness is collateral with respect to ride, this aspect, together with the psycho-physical perception and the effects of the design of the seats and vehicle interiors, will not be part of this review. Similarly, the frequency ranges higher than ∼25 Hz deal with the noise, vibration and harshness (NVH) field [14,15], and are considered out of scope.

A vehicle with good ride quality should: (i) attenuate the occupants' perception of road irregularities; (ii) enable desirable road holding; and (iii) attenuate the vehicle body motions excited by the driving actions, i.e. by traction/braking and cornering, and enhance the related occupants' perception. (i) – (iii) are crucial to the subjective driver confidence [11], which is key especially in high-performance passenger cars. For example, through appropriate ride design, even a sub-optimal handling performance may be perceived as appealing by the driver, which is a primary target for car makers [4].

In the vehicle design process, the sensations perceived by the driver and passengers, namely their subjective feedback, should be correlated with the objective metrics defined by the development engineers, thus indicating what can be modified or tuned at the vehicle or component level. In the automotive industry, the ride quality assessment is performed through:

- Objective metrics, here also referred to as key performance indicators (KPIs), derived from either simulations or experimental measurements along specified manoeuvres, performed on real test tracks/roads or post-rigs.
- Subjective attributes, according to which the evaluation is based on the driver's (and potentially passengers') feedback through subjective scores, while driving a real vehicle, or a virtual one on a road scenario simulator.

Although many publications are available on the previous topics, including a few reviews [2], [4], [13] and a standard [5], to the best of the author's knowledge, the literature misses a thorough review with:

(1) A detailed description of the objective metrics for ride quality assessment.
(2) The objective performance assessment methodology, including typical manoeuvres, road profiles, vehicle instrumentation set-up, and objective KPIs.
(3) A semantic description of the subjective attributes for ride quality assessment, which is not comprehensively available, since this is usually associated with the internal know-how of Tier 1 suppliers and car makers.
(4) A proposal for unifying the nomenclature of the subjective attributes, since each company has its internal one, and different definitions from the literature often indicate the same attribute.
(5) A systematic description of the approaches for correlating objective and subjective metrics.

The goal of this literature survey is to bring the reader up to speed with the relevant research and technical concepts in the field of ride quality assessment, by considering references – in the form of papers, dissertations, and standards – in English language only.

The manuscript is organised according to the typical assessment workflow in Figure 2, i.e.: Section 2 covers the objective evaluation, by discussing the relevant manoeuvres and the main performance indicators, together with the required vehicle instrumentation; Section 3 describes the subjective evaluation process, starting from the definition of the subjective attributes, following with the assessment methods and questionnaires, mainly derived from the current standards, and usually provided to professional drivers for the evaluation; Section 4 highlights the methods to efficiently correlate objective metrics and subjective attributes for vehicle design and development; finally, Section 5 summarises the main conclusions.

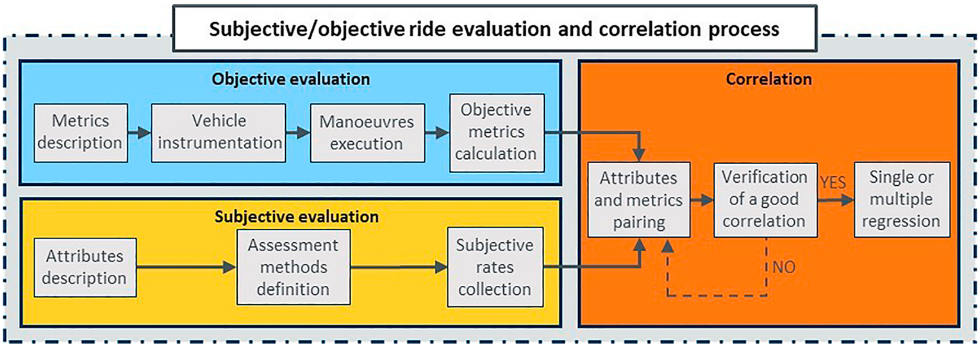


Figure 2. Typical workflow diagram for the objective and subjective evaluation of vehicle ride quality, including possible correlation of the respective results.

2. Objective evaluation

The objective testing phase is strictly required to assess the performance without the inevitable errors generated by the human evaluation. The objective evaluation of a vehicle ride quality is carried out through tests in which pre-defined variables are experimentally measured or obtained through simulations, to evaluate the ride KPIs, i.e. the objective metrics.

2.1. Manoeuvres and road profiles

The considered road profiles are usually classified into single obstacle type road profiles and long type road profiles, see [16]. The assessment is performed through physical vehicles or simulation models, in the latter case with or without the presence of a driver in the loop. In case of physical vehicle testing, the experiments can involve vehicle operation on a real road profile, or the use of a post-rig. In the tests involving real vehicles, it is important to know the road input characteristics, namely amplitudes and wavelengths, to extract the level of excitation. This information is generally available along the dedicated test tracks of automotive proving grounds, but there are cases in which the road information is not accessible.

Bumps, cleats, and potholes are the most typical examples of profiles under the single obstacle type category. A bump is a raised area built across a road to slow down the traffic, and is the most frequently selected single input obstacle in the literature. Bumps cross the entire roadway, and can have different shapes and dimensions, depending on the standards of each country [16,17], [22–24]. The tests on bumps are usually performed for vehicle speeds ranging from 20 to 60 km/h, to allow ride quality assessment in specific frequency ranges. The dimensions of a bump, usually from $\sim$0.05 to $\sim$0.125 m in height and from $\sim$0.85 to $\sim$10 m in length, play a critical role in determining the frequency ranges to be excited [25–27]: bumps with greater length and height are employed to excite lower frequencies, namely primary ride, whilst smaller bumps excite higher frequencies, and are relevant to secondary ride. Another common test is the impact on a cleat, which is a straight bar placed on a flat road, perpendicular to the direction of travel. This profile is mainly used for secondary ride assessment [4], [16], [28]. Additionally, some authors implement impulsive tests with negative inputs, frequently referring to them as pothole or manhole tests [16], [27]. For example, Canale et al. [29] define their case study pothole as a drain well, characterised by a depth of 0.05 m and a width of 0.6 m. The step road profile test is another possible single obstacle input that is sometimes adopted [30–32].

The long-type road tests may involve real/realistic profiles available on public roads, which can be grouped into: (i) flat roads; (ii) Belgian blocks and similar; and (iii) uneven roads. Flat roads include highways [16], [33], motorways [22] and freeways [28], surfaced with asphalt concrete [22], [34] or cement [7]. Such a type of roads is mainly used to evaluate secondary ride. The inputs of these roads with different roughness characteristics are considered to be stochastic. Hence, the length of the acquisition must be sufficiently long to get representative results. The tests on flat roads are performed with an instrumented car at different speeds, typically ranging from ~ 40 to ~ 140 km/h [33]. Another method to assess secondary ride, and sometimes harshness as well, is to drive the vehicle on corrugated roads, such as Belgian blocks, paved roads, and cobblestone roads [16], [22], [33–36]. The terms Belgian blocks and paved roads are usually referred to roads paved with square-shaped blocks of different sizes, whilst cobblestone roads are paved with round-shaped blocks [22]. The blocks extrude from the base of the pavement with different heights, implying that the resulting excitation can have variable amplitude. Uneven roads or rough roads have profiles with elevation changes that excite the primary and secondary rides, and, in some cases, even the NVH region. For example, Canale et al. [29] define this type of road profile as English track, while other authors [33], [36,37] use different denominations for the same concept, e.g. they refer to them as bumpy roads. The profiles are typically characterised by spaced irregularities, such as bumps and potholes. These obstacles can be located to cause an in- or out-of-phase response of the left and right unsprung masses [37]. The vehicle speed is typically held constant to ensure the excitation of specific frequencies [4]. Sinasac [4] and Ghanwat et al. [7] use bumpy roads to evaluate primary ride, and therefore they select just the part of these roads provoking low frequency excitations.

In the simulation analyses, the road profiles [25–27], [29], [38,39] are often virtually developed by using the so-called ISO roads profiles derived from the standard ISO 8608 [40], which provides the information for the reproduction of theoretical road classes based on roughness.

The road excitation can be also experimentally reproduced at the vehicle level on a 4- or 7-post rig, where displacement of the road profile is defined by a function, with constraints and limitations set by the capability of the specific facility. In the scientific literature, the most common post rig based assessments are sine sweep tests, in which the frequency of road excitation is gradually increased [41–44]; in rare cases, a sinusoidal function with constant amplitude and frequency is used [30].

The ride tests above are usually conducted at constant speed in a straight line. Nevertheless, the ride comfort assessment can include manoeuvres involving cornering and/or hard acceleration and braking, which are typically used to evaluate handling and stability, but can also be adopted for road holding and ride comfort evaluation. This is especially relevant to high-performance passenger cars, as they are usually characterised by a rather sporty use. Thus, the ISO double lane change from the standard ISO 3888 [45,46] is a manoeuvre frequently used to assess the vehicle roll behaviour and its impact on ride quality [4], while another common manoeuvre is the sine sweep steer test [4], [47], in which a steering input of constant magnitude is applied at increasing frequency.

2.2. Objective metrics

The procedures to objectively assess the ride quality are defined in the standards BS 6841:1987 [48] and ISO 2631-1:1997 [49]. The available objective metrics for primary and secondary ride are listed in Table 1, including the denomination and formulation of the KPIs, together with the references in which they have been used. The main symbols of the variables in Table 1 are reported in Figure 3, including indication of the relevant accelerations, speeds, and displacements of the sprung mass and unsprung masses.

The ride comfort KPIs are mainly based on the vertical accelerations recorded along time, t, in different sections of the vehicle. The absolute peak, $\ddot{z}_{s_{max}}$, and the peak-to-peak value, $P2P$, of the vertical acceleration of the sprung mass are the most frequently selected indicators for assessing performance during isolated events, such as those of single obstacle type roads. As an example, Figure 4(a) highlights these KPIs along the vertical acceleration profile of the sprung mass, for a single input test. In particular, $P2P$ indicates the maximum variation of the impulsive accelerometric signal, a, and can be additionally evaluated on the angular body accelerations, namely the pitch, $\ddot{\theta}$, and roll, $\ddot{\phi}$, accelerations, and on the unsprung mass vertical accelerations, $\ddot{z}_u$. The time history of the sprung mass vertical displacement, z_s, is also considered [50] in single obstacle type road tests, e.g. to compute the maximum value and the third positive peak of the vertical displacement of the sprung mass, respectively $z_{s_{max}}$ and $z_{s_{nod}}$. In particular, $z_{s_{nod}}$ provides an indication of the decay of the oscillations [25]. The transient response after a road step input can also be evaluated through the following KPIs, usually referring to the sprung mass displacement, even if in rare cases they are applied to other variables, such as speeds and accelerations: (i) the overshoot, OS, i.e. the difference between the maximum and steady-state values of the considered variable; (ii) the response time, $t_{Response}$, i.e. the time from the start of the event, t_0, to the time for the system to reach 90% of its steady-state condition, $t_{90\%_{ss}}$; (iii) the settling time, $t_{Settling}$, i.e. the time from the input application to when the considered variable remains within a specified error band, typically $\pm 5\%$ of the steady-state value, e_{SS}; and (iv) the rise time, t_{Rise}, i.e. the time to transition from the 10%, corresponding to the time instant $t_{10\%_{ss}}$, to the 90%, corresponding to $t_{90\%_{ss}}$, of the steady-state value of the variable.

In single obstacle type roads, the metrics above are often combined with the root mean square values, RMS, of the accelerations measured over a time period T, see Figure 4(b). The RMS, which is also the main indicator for long type road profiles, captures both the positive and negative values of the considered acceleration. The RMS based indicators are calculated either in the time domain, directly from the acceleration signal, or in the frequency domain, f, starting from the power spectral density, $P(f)$, of the acceleration, along a specified frequency range, from f_1 to f_2, see Figure 4(c), based on the road excitation [4]. In rare cases, the acceleration values are normalised with the gravitational acceleration g, thus giving origin to the normalised root mean square value, $NRMS$.

Many papers use the weighted root mean square value of the acceleration, $WRMS$, which is described in the standards BS-6841 [48] and ISO-2631 [49]. The $WRMS$ is the RMS value of the frequency-weighted acceleration a_w, which is obtained by applying frequency-dependent filtering functions to the unweighted acceleration. If the vibrational inputs are applied in more than one direction, the vibration total value of the $WRMS$ acceleration, namely a_v, is more appropriate, since its formulation is based on the linear combinations of the vibrations in orthogonal coordinates, with three multiplying factors, i.e. k_x, k_y, and k_z.

Table 1. Summary of the main metrics (KPIs) for the objective evaluation of vehicle ride quality.

KPI	Definition	Reference
Maximum value of the vertical displacement of the sprung mass	$z_{s_{max}} = \max \|z_s(t)\|$	[2], [25]
Maximum value of the vertical body acceleration of the sprung mass	$\ddot{z}_{s_{max}} = \max \|\ddot{z}_s(t)\|$	[2], [17], [25], [29], [51]
Third positive peak of the vertical displacement of the sprung mass	$z_{s_{nod}}(t)$	[2], [25]
Peak-to-peak value of the relevant acceleration, *a*, of the sprung mass (linear or angular)	$P2P = \max(a(t)) - \min(a(t))$	[2], [4], [16], [28], [51], [53]
Overshoot	$OS = e_{max} - e_{ss}$	[4]
Response time	$t_{Response} = t_{90\%_{ss}} - t_0$	[4]
Settling time	$t_{Settling} = t_{\pm 5\%_{ss}} - t_0$	[4], [16]
Rise time	$t_{Rise} = t_{90\%_{ss}} - t_{10\%_{ss}}$	[4]
Root mean square (*RMS*) value of the accelerations	$RMS = \sqrt{1/T \int_T a^2(t)dt}$	[2], [4–7], [16], [18], [25,26], [28–30], [33,34], [38,39], [41], [47,48], [51], [54–57]
	$RMS = \sqrt{\int_{f_1}^{f_2} P(f)df}$	
RMS value of the normalised vertical acceleration of the sprung mass	$NRMS = \sqrt{1/T \int_T (\ddot{z}_S(t)/g)^2 dt}$	[29], [31]
Weighted *RMS* acceleration	$WRMS = \sqrt{1/T \int_T a_W^2(t)dt}$ $WRMS = \sqrt{\int_{f_1}^{f_2} W^2(f)P(f)df}$	[22], [27], [31], [37], [51], [58–62]
Point vibration total value	$a_v = (k_x^2 a_{W,x}^2 + k_y^2 a_{W,y}^2 + k_z^2 a_{W,z}^2)^{\frac{1}{2}}$	[2], [22], [48,49], [51], [62]
Running *RMS* value of the weighted acceleration	$RWRMS = \sqrt{1/\Delta T \int_{t_1}^{t_1+\Delta T} [a_W(t)]^2 dt}$	[2], [16], [48,49], [51,52]
Maximum transient vibration value	$MTVV = \max(a_W(t))$	[2], [48,49], [51,52]
Root mean quad accelerations	$RMQ = \sqrt[4]{1/T \int_T a^4(t)dt}$	[2], [13], [34], [38], [63]
Vibration dose value	$VDV = \int_0^T [a^4(t)dt]^{1/4}$	[2], [13], [33], [37,38], [52], [58], [63,64]
Equivalent weighted acceleration	$a_{w,e} = \left(\sum a_{w,i}^4 T_i / \sum T_i\right)^{1/4}$ or $a_{w,e} = \left(\sum a_{w,i}^2 T_i / \sum T_i\right)^{1/2}$	[22], [43]
Estimated vibration dose value	$eVDV = 1.4 a_{w,e} T^{1/4}$	[43,44], [63]
Effective amplitude transmissibility of the seat	$Seat(\%) = (VDV_{Seat}/VDV_{Floor})100$	[34], [58], [62], [64]
Root integral of the suspension deflection	$\sigma_{SD} = \sqrt{\int_{f_1}^{f_2} P(f)df}$	[17]
RMS value of the suspension deflection	$RMS_{SD} = \sqrt{1/T \int_T (z_{s_{ij}} - z_{u_{ij}})^2 dt}$	[17], [26]
Suspension working space	$SWS = \max(z_{s_{ij}} - z_{u_{ij}}) - \min(z_{s_{ij}} - z_{u_{ij}})$	[4], [42], [56]
RMS value of tyre deflection	$RMS_{z_u} = \sqrt{1/T \int_T z_t^2(t)dt}$	[57]
RMS value of the normalised dynamic wheel load	$RMS_{\Delta F_z} = \sqrt{1/T \int_T (F_z(t) - F_{z,0})^2 / F_{z,0}^2 dt}$	[25], [30], [43], [47]

The *RMS* values and all the other derived formulations are appropriate for stationary signals, i.e. waveforms that, from a statistical viewpoint, have constant mean and variance, but they can be misleading when non-stationary vibrations are considered [13]. Therefore,

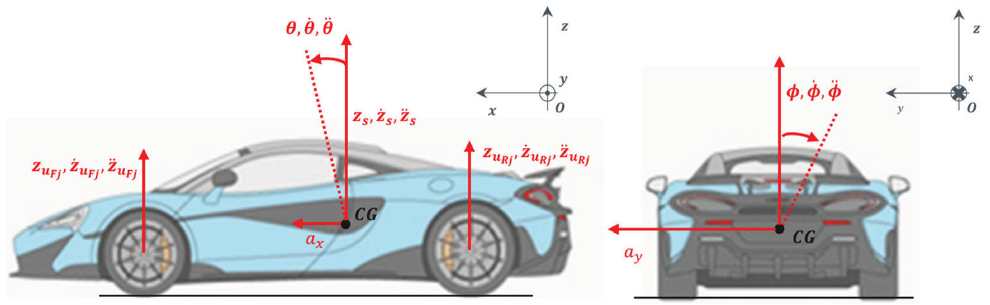


Figure 3. Lateral and rear views of a vehicle, showing the main variables considered in the computation of the objective metrics: (i) heave (z_s, $\dot{z}_s$, $\ddot{z}_s$), roll (ϕ, $\dot{\phi}$, $\ddot{\phi}$) and pitch (θ, $\dot{\theta}$, $\ddot{\theta}$) displacements, speeds, and accelerations of the sprung mass; (ii) longitudinal and lateral accelerations of the vehicle (a_x, a_y); and (iii) vertical displacements, speeds and accelerations ($z_{u_{ij}}$, $\dot{z}_{u_{ij}}$, $\ddot{z}_{u_{ij}}$) of the unsprung masses of the four corners, where the subscript $i = F, R$ indicates the front or rear axles, and the subscript $j = L, R$ the left or right vehicle sides.

the crest factor, CF, is used by the standards to distinguish between stationary and non-stationary signals, according to [48]:

$$CF = \frac{a_{W,max}}{WRMS} \tag{1}$$

with $a_{W,max}$ being defined as the maximum instantaneous peak value of the weighted acceleration. When CF is less than 6, the signal used for its calculation is considered stationary, whilst for CF values higher than 6 the signal is deemed non-stationary. For $CF > 6$, a suitable KPI is the running weighted root mean square acceleration, $RWRMS$, which corresponds to the square of the weighted acceleration peak recorded during an observation time ΔT (Figure 4(b)). The maximum transient vibration value, $MTVV$, is also rarely used for non-stationary events. Metrics that are similar to the $RWRMS$ are the root mean quad, RMQ, the vibration dose value, VDV, and the estimated vibration dose value, $eVDV$ [49], all of them using the fourth power of the weighted acceleration. A fourth power vibration dose index is more sensitive to the peaks than an RMS averaging method.

The seat factor, *Seat*, expressed in percentage, allows differentiating the vibration levels, defined by the VDV, at the driver or passenger floor, from those at the seat-pad. A 100% *Seat* value implies that the seat does not lead to any benefit in terms of vibration mitigation with respect to the floor; values lower than 100% refer to a comfort improvement, whilst values above 100% imply reduced vibrational comfort.

When evaluating ride quality, especially for high-performance passenger cars, it is necessary to consider also KPIs of the road holding capability. In this case, the indicators rely on the availability of the suspension displacement measurement, and the estimation of the vertical loads on each corner. For example, relevant metrics include the root integral, σ_{SD}, over a specified frequency band, of the power spectral density of suspension deflection, and the RMS value of the suspension deflection over a time window, RMS_{SD}. Another relevant metric is the suspension working space, SWS, which measures the maximum suspension travel during the manoeuvre. Low values of these metrics tend to imply better performance. A fundamental factor for road holding is the fluctuation of the vertical tyre load, which is

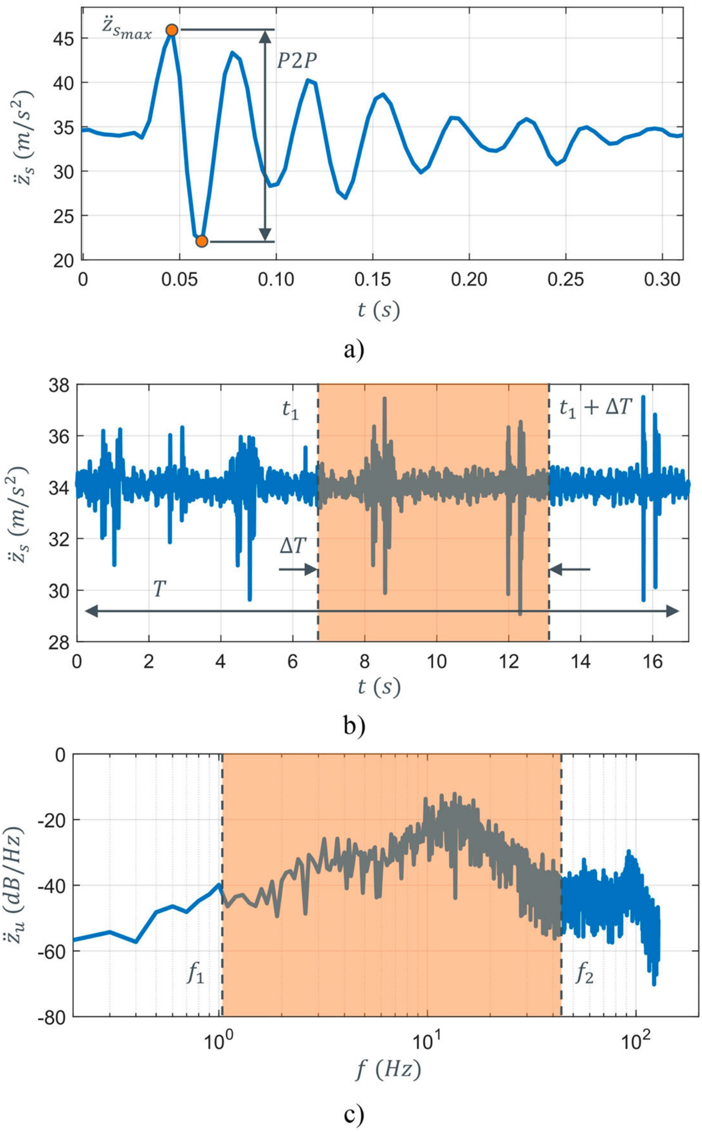


Figure 4. Examples of explanatory graphs for a selection of the discussed KPIs, by using signals experimentally recorded by McLaren Automotive on a test vehicle: a) time profile of the heave acceleration for a road step input at low speed; b) time profile of the heave acceleration on an uneven road surface; and c) power spectral density of the vertical acceleration of an unsprung mass in the frequency domain, on an uneven surface.

related to the capability of the tyre to generate longitudinal and lateral forces in transient conditions. The load fluctuations are often measured through: (i) the root mean square value, $RMS_{\Delta Fz}$, of the normalised dynamic wheel load, $(F_z - F_{z,0})/F_{z,0}$, where F_z is the current vertical tyre force, and $F_{z,0}$ is the respective static load; or (ii) the RMS value of the vertical tyre deflection, RMS_{z_t}. Lower values of these metrics correspond to improved dissipation of road disturbances and road holding ability, namely better grip.

Table 2. Overview of manoeuvres and road profiles, with the related performance indicators.

Metric type	KPI	Manoeuvre / road profile	References
Ride comfort	$z_{s_{max}}$	Bump	[25]
	$\ddot{z}_{s_{max}}$	Bump	[17], [25], [29]
		Hole	[29]
	$z_{s_{nod}}(t)$	Bump	[25]
	$P2P$	Cleat	[4], [28]
		Bump	[16], [53]
	OS	Cleat	[4]
	$t_{Response}$	Cleat	[4]
	$t_{Settling}$	Cleat	[4], [16]
	t_{Rise}	Cleat	[4]
	RMS	Bump	[41]
		Cleat	[28]
		Step	[26]
		Hole	[29]
		Flat road	[7], [16], [28], [33,34], [42]
		Cobblestone road	[16], [34]
		Belgian blocks	[33,34], [54]
		Uneven road	[4–7], [16], [33,34], [54]
		ISO roads	[25,26], [38–41]
		Sinusoidal road input	[30], [41–43], [56]
		Lane change	[4], [47]
		Swept sine steer	[47]
	$NRMS$	Hole	[29]
		Uneven roads	[29]
		ISO roads	[29], [31]
	$WRMS$	Bump	[22]
		Flat road	[22]
		Cobblestone road	[22]
		Belgian blocks	[22]
		Uneven roads	[37]
		ISO roads	[27], [29], [31]
		Swept sine steer	[58]
	$RWRMS$	Uneven roads	[16], [52]
	RMQ	Flat road	[34]
		Cobblestone road	[34]
		Belgian blocks	[34]
		Uneven road	[34]
		ISO roads	[38]
	VDV	Flat road	[33], [64]
		Belgian blocks	[33]
		Uneven road	[33], [37]
		ISO roads	[38]
		Swept sine steer	[58]
	$a_{w,e}$	Sinusoidal road input	[43,44]
	$eVDV$	Sinusoidal road input	[43,44]
	$Seat$	Flat road	[64]
		Swept sine steer	[58]
Road holding	σ_{SD}	Bump	[17]
		Flat road	[17]
	RMS_{SD}	Bump	[17]
		Flat road	[17]
		ISO roads	[26]
	SWS	Cleat	[4]
		Uneven road	[4]
		Sinusoidal road input	[42], [56]
	$RMS_{\Delta F_z}$	Bump	[25]
		Step	[30]
		ISO roads	[25]
		Sinusoidal road input	[30], [42,43]
		Lane change	[47]
		Swept sine steer	[47]

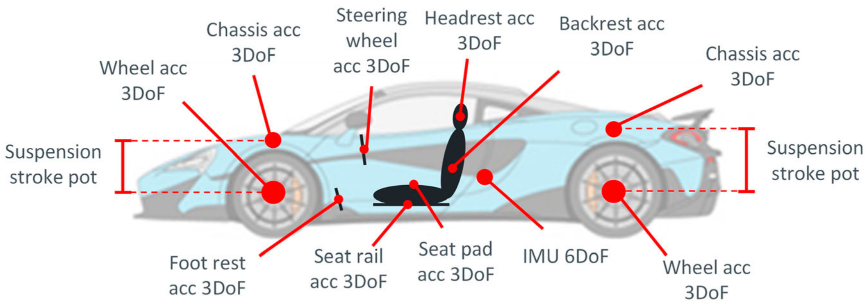


Figure 5. Schematic representation of the typical vehicle instrumentation set-up to measure the signals required for the calculation of the objective KPIs. 'acc': accelerometer; 'pot': potentiometer; 'DoF': degree-of-freedom.

The discussed KPIs have different purposes, and are not universally applicable to every type of manoeuvre and road profile. For example, a primary differentiation exists between the KPIs for evaluating ride comfort and those for road holding. In terms of ride comfort assessment, the selection of KPIs is mainly influenced by the road profile characteristics. Table 2 presents how the available studies have associated the metrics with the manoeuvres and road profiles.

2.3. Measurement equipment

The vehicle performance measurement equipment is of fundamental importance, as meaningful measurements are the basis for correct data post-processing, and the computation of the objective metrics. A good knowledge of the instrumentation specifications also contributes to improving the quality of the experimental validation of the ride simulation models. In fact, with the most recent generation of commercially available simulation models, such as Vi-CarRealTime and CarMaker, it is possible to accurately emulate sensors with the respective errors and delays, and place them in the simulated vehicle, in the same location as on the real vehicle.

In the most general and extensive form, Figure 5 includes the set of sensors that are required for a complete ride analysis:

- Triaxial accelerometers, which are typically installed on each unsprung mass, see Figure 6 and [5], [7], [17], [23], [33], [53], [64], and the top mount of each suspension, see the examples in [5], [7], [17], [23], [33], [53].
- Linear potentiometers between each unsprung mass and the vehicle body, to measure damper/spring displacement, see Figure 6 [7], [17], [53], [64].
- A 6DoF inertial measurement unit (IMU), which measures the three accelerations and three angular speeds of the sprung mass. The IMU consists of a triaxial accelerometer and a triaxial gyroscope, and is generally installed close to the vehicle centre of mass [5], [16,17], [22], [33], [64,65]. Rarely, a GPS (global positioning system) sensor is used to measure the longitudinal vehicle speed [5], [16], [22], [64].

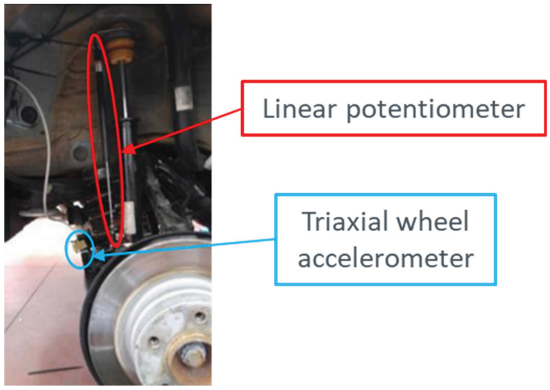


Figure 6. Example of installation of a linear potentiometer and a triaxial accelerometer on the suspension system of a case study vehicle (from [17]).

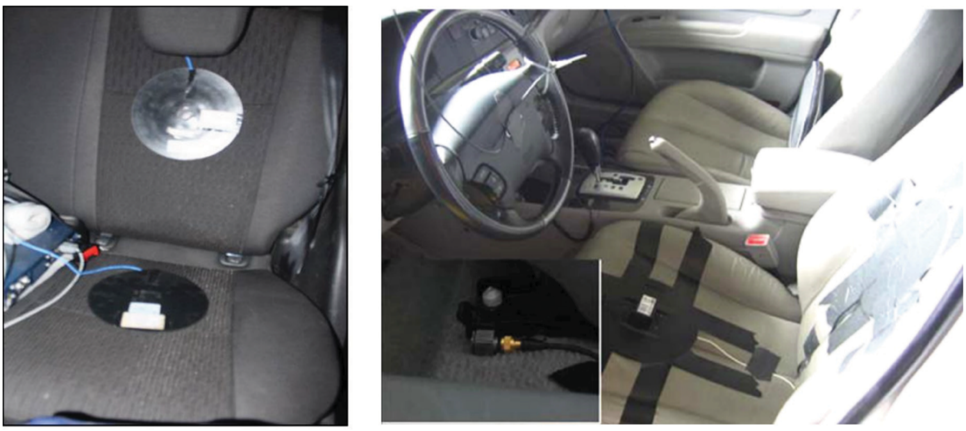


Figure 7. Examples of installation of accelerometers on: a) the seat pad and backrest [64]; and b) the footrest and steering wheel [34].

In the driver and/or passenger interface areas, sensors can be installed (Figure 7) to measure the accelerations in different positions, including:

- The seat, where triaxial accelerometers can be placed at the seat rail [5], [7], [16], [28], [52], seat pad [5], [7], [13], [16], [23], [33,34], [37], [52], [64], seat floor [5], [7], [33,34], backrest [5], [16], [28], [33], [34], [52], [64], and rarely the headrest [13].
- Footrest, where a triaxial accelerometer can be located near the brake pedal to evaluate the driver's feet accelerations [5], [7], [16], [33], [64].
- Steering wheel [5], [16], [33], where the sensor is usually installed on the upper semi-circumference.

Typical specifications of accelerometers for vehicle ride measurements are included in Table 3. The standard ISO 15037-3:2022 [5] states that the band of human sensitivity ranges from 0 to 100 Hz, but the frequency range relevant to the ride comfort of passenger cars is

Table 3. Examples of performance characteristics of typical accelerometers for ride comfort measurement [16], [18], [22], [52], [66].

Manufacturer, sensor model	Input range (g)	Frequency response (Hz)	Sensitivity (mV/g)
Silicon Design, SDI-1 2210	±10	0–1100 (Typ., ±3 dB) 0–660 (Min., ±3 dB) 0–700 (Typ., 5%)	400
PCB Piezotronics, 3713E 1125G	±25	0–1500 (Nom., ±3 dB) 0–750 (Min., ±3 dB)	80
Dytran Instruments, 7556A1	±3	0–800 (Nom., ±3 dB)	400
SensorWay Measurement Technology, Entran EGCS3-A	±10	0–200 (Nom., ±1 dB) 0–120 (Nom., ±2 dB)	500
Brüel & Kjær, Triaxial DeltaTron 4525	±50	0–1000 (Typ., ±10%)	100
Kistler, 8763B050BB	±50	0.5–7000 (Nom., ±5%) 0.3-1000 (Nom., ±10%)	100

between 0 and 50 Hz. As a consequence, the standard also states the transducer bandwidth should be higher than 500 Hz, and the amplitude errors less than ±0.5%.

3. Subjective evaluation

There are multiple alternative approaches to the subjective evaluation of ride quality. In the literature, some authors simply ask the drivers whether they feel the vehicle to be comfortable throughout the testing phase [16], [34], [37], [67]. However, especially for high-performance and/or high-segment passenger cars, the car makers tend to evaluate ride quality in detail, through sophisticated subjective attributes targeting well-defined aspects. The attributes consist of the qualitative descriptions of specific vehicle behaviours that are subjectively assessed in the testing phase, through numerical assessment (scoring) by the driver and/or passengers. Hence, the attributes are the subjective equivalent of the objective KPIs. The following sub-sections list typical attributes for primary and secondary ride. The names and descriptions are derived from the literature as well as the industrial and research experience of the authors.

3.1. Subjective attributes for primary ride

The main aspects included in typical subjective primary ride assessments, together with the respective attributes, are:

- **Aspect 1: isolation from the road inputs** [6], which assesses the perceived comfort level associated with the sprung mass motions excited by various typologies of uneven roads. This aspect involves consideration of multiple attributes, accounting for each motion of the sprung mass:
  - **Pitch control**, which evaluates the body pitch motion caused by the out-of-phase vertical motions of the front and rear axles. In general, within a subjective assessment framework, body control is the perceived capability of compensating the external road excitation. The pitch control attribute is typically considered on uneven road surfaces with small frequency undulations [7], [10], [64]. For a correct evaluation, the driver may be specifically instructed to assess the so-called harmony, i.e. the response delay between the front and rear axles.
  - **Vertical ride control** [4] **or bounce** [7] **control**, which refers to the perceived magnitude of the heave motions [10], [52], [64].

- ○ **Road copying**, which evaluates the user perception of the vehicle ability to minimise the roll motions [10], [64], since road irregularities are not necessarily symmetrical, and the tyres on the two vehicle sides can be subjected to different road excitations, provoking a roll motion of the vehicle body.
- **Aspect 2: response to large excitations**, which targets the subjective assessment of the vehicle body oscillations along manoeuvres on single obstacle road profiles. In the industrial practice, two attributes are mainly used, depending on the nature of the road excitation event:
  - ○ **Topping**, which evaluates the vehicle body control quality over a crest, i.e. a localised road input inducing an upward motion of the sprung mass.
  - ○ **Bottoming**, which evaluates the vehicle body control performance during grounding events, i.e. in which the road inputs induce a downward motion of the sprung mass.
- **Aspect 3: pitch under braking/acceleration** [6], which is similar to Aspect 1, but is evaluated in acceleration and/or braking conditions on flat roads [7]. The assessment is typically based on the combination of two attributes:
  - ○ **Pitch abruptness**, evaluating the magnitude of the pitch motion [4].
  - ○ **Pitch delay**, associated with the time the pitch angle takes to reach its steady-state value [4].

3.2. *Subjective attributes for secondary ride*

The main subjective attributes for secondary ride assessment are:

- **Bobbing vibration** [7] **or choppiness** [2], [50] **level**, which includes the harmonic body vibrations induced by the eigenmodes of the unsprung masses and powertrain/s, in the $\sim$5–10 Hz range, and is typically evaluated on cement roads at different vehicle speeds, in the 60–80 km/h range [7]. The attribute targets the vertical and longitudinal low-amplitude vibrations experienced by the vehicle body, which give the impression that the sprung and unsprung masses move in-phase. The occupants tend to perceive these vibrations especially in their abdominal masses.
- **Shake or choppy vibration level** [2], [6,7], [50], which covers the harmonic body vibrations induced by the eigenmodes of the unsprung masses, powertrain/s and steering column, in the $\sim$10–25 Hz range. Shake vibrations refer to high-frequency low-amplitude vibrations, typically excited by road surfaces characterised by plenty of small cracks. These vibrations mainly stress the calves and thighs of the passengers, and sub-attributes can be used to differentiate the assessment of the vibration, based on the human machine interface transmitting the vibration and the perceived source of vibration, e.g.:
  - ○ **Body floor shake** induced by the suspension systems.
  - ○ **Seat shake** vibration provoked by the driveline.
  - ○ **Steering wheel shake** induced by shimmy propagated through the steering column.

  Attributes are available to evaluate the scenario of single obstacle road profiles as well:

- **Small impact response** [2], [6], [52], which evaluates the magnitude of the vehicle body impact acceleration over small positive/negative discrete road inputs ($<$ 15 mm), while driving the vehicle at different speeds.

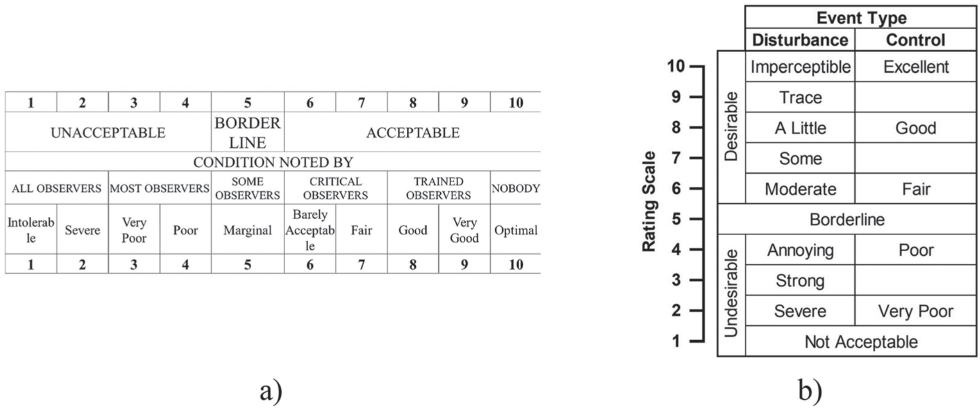


Figure 8. SAE rating scales for subjective evaluation, from: a) J1060 [68]; and b) J1441 [69].

- **Large impact response** [2], [6], [52], which refers to the magnitude of the vehicle body impact acceleration over large positive/negative discrete inputs ($>$ 15 mm), at different vehicle speeds. Aspects that can be individually scored are:
  - **Front or rear axle response**, related to the chassis acceleration peak after a front or rear axle impact.
  - **Single wheel response**, referring to the chassis acceleration peak after a single wheel impact.
  - **Driver disturbance** [4], chassis acceleration peak at the seat, after an impact.
- **Disturbance dissipation** [4], [64], which assesses how quickly the vertical vehicle motion dissipates after hitting an obstacle, and – similarly to the large impact response – can be independently evaluated at the level of the front axle, rear axle, or individual wheel.

3.3. Assessment methods

Although a variety of scoring procedures are used in the literature, the most widely adopted methodologies derive from the SAE standards J1060 [68] and J1441[69], which establish rating scales for subjective assessment. Both scales range from 1 to 10, see Figure 8, and, although normally the ratings are integer, also decimal figures can be included in the scores. The performance is considered acceptable or desirable if the rating is in the range between 5 and 10, whilst a rating between 1 and 5 is considered unacceptable or undesirable; and a rating of 5 highlights borderline performance. Every integer value on the rating scale corresponds to an adjective, which expresses the ultimate evaluation by the occupant/s. In the table from J1441, the term ‘disturbance’ refers to ride evaluation, while ‘control’ refers to handling assessment.

Rarely, authors employ alternative scoring techniques. For example, in Mansfield et al. [37], the drivers were asked to give a ride comfort score on a seven-point scale, with 1 being ‘comfortable’ and 7 being ‘uncomfortable’. In Bennett [10], the evaluation is conducted only through adjectives.

As stated in J1441 [69], it is important to consider the type of driver who is performing the tests. Especially for high-performance cars, the vehicle ride evaluation is usually carried out by a jury consisting of a small group of expert evaluators who are familiar with the needs and expectations of the target customer. Non-expert drivers are also involved, but in this case a larger jury size is necessary for meaningful results, because of the increased scatter in the ratings. External conditions, such as weather and varied road conditions, as well as the composition of the jury, can have an impact on the evaluations. Therefore, it is crucial to ensure that all the members are exposed to identical testing conditions. This can be accomplished through a simulator rather than a real vehicle [4].

During subjective testing, it is common to consider the anthropometric data of the jury panel members, such as height, weight and age [34], [37], [43], [52], [64], [67], [70], and, in some case [52], the value of their body mass index, *BMI*:

$$BMI = \frac{m}{h^2} \tag{2}$$

where m and h are the mass and height of the person. The data related to the body differences and genders has an impact on the ride comfort perception [2], [7], [34], [43], [52], and can be used to justify possible outliers and subjective score dispersion.

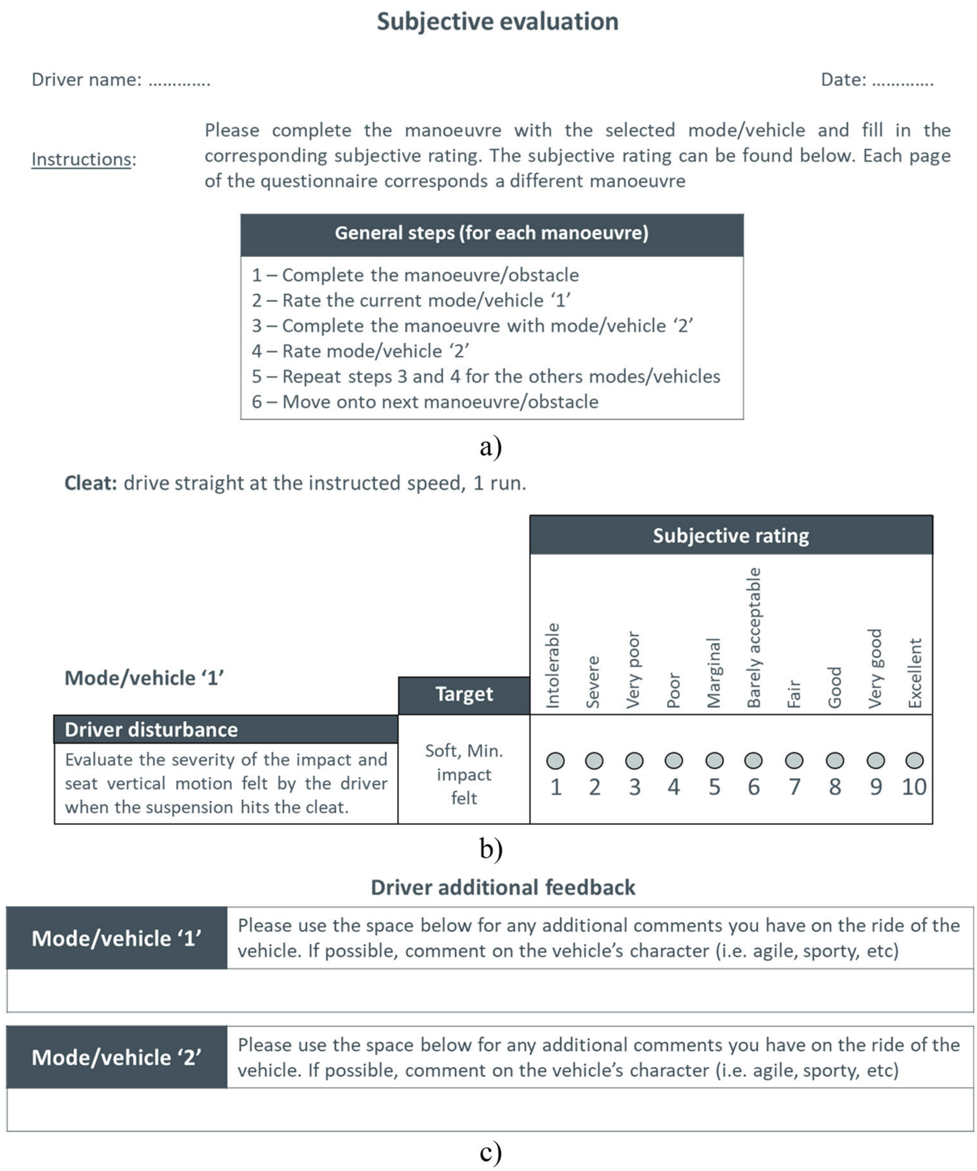
Sinasac [4] provides one of the most accurate descriptions of a subjective evaluation procedure for semi-active suspension tuning. In general, the scoring is based on a questionnaire form (Figure 9) to be filled in at the end of the test, which includes the list of subjective attributes, the rating scale, and the information for the execution of the tests.

Based on [4] and the industrial experience of the authors, the typical subjective evaluation method involves the following steps:

(1) **General briefing**, consisting of an introduction of the rules and procedures to be followed in the execution of the tests, and a description of the questionnaire, with an overview of the rating scales and subjective attributes.
(2) **Subjective evaluation**, during which one driver at a time enters the vehicle with a pen and the questionnaire or a laptop/smartphone, and drives the car through the first manoeuvre with the default configuration setting, which is the baseline used for rating consistency [69]. After his/her evaluation, the driver repeats the same manoeuvre with different tunings of the same vehicle, or different vehicles. Once all manoeuvres have been performed, the drivers discuss the subjective scores assigned to the different vehicle settings with the engineers.
(3) **Post-processing**, in which the rating values are plotted for all tested configurations, along with their mean and standard deviation values, and compared with each other.

4. Subjective and objective correlation

The ride dynamics and respective assessment play an important role in the vehicle design process. Current approaches are generally focused on a first objective evaluation along standardised manoeuvres, and afterwards on the subjective assessment of certain vehicle ride features. The subjective-objective correlation is taking increasing importance, since it gives the possibility of predicting the subjective evaluation, which is the ultimate output of the process, directly from the objective performance indicators. A proper correlation based



Subjective evaluation

Driver name: .... Date: ....

Instructions: Please complete the manoeuvre with the selected mode/vehicle and fill in the corresponding subjective rating. The subjective rating can be found below. Each page of the questionnaire corresponds a different manoeuvre

General steps (for each manoeuvre)
1 – Complete the manoeuvre/obstacle 2 – Rate the current mode/vehicle ‘1’ 3 – Complete the manoeuvre with mode/vehicle ‘2’ 4 – Rate mode/vehicle ‘2’ 5 – Repeat steps 3 and 4 for the others modes/vehicles 6 – Move onto next manoeuvre/obstacle

a)

Cleat: drive straight at the instructed speed, 1 run.

Mode/vehicle ‘1’

Driver disturbance	Target	Intolerable	Severe	Very poor	Poor	Marginal	Barely acceptable	Fair	Good	Very good	Excellent
		Subjective rating									
Evaluate the severity of the impact and seat vertical motion felt by the driver when the suspension hits the cleat.	Soft, Min. impact felt	1	2	3	4	5	6	7	8	9	10

b)

Driver additional feedback

Mode/vehicle ‘1’	Please use the space below for any additional comments you have on the ride of the vehicle. If possible, comment on the vehicle’s character (i.e. agile, sporty, etc)
Mode/vehicle ‘2’	Please use the space below for any additional comments you have on the ride of the vehicle. If possible, comment on the vehicle’s character (i.e. agile, sporty, etc)

c)

Figure 9. Example of subjective evaluation questionnaire template, extracted and adapted from Sinasac [4]: a) first page, which displays the general instructions for the evaluation method, including the order and details of the manoeuvres; b) following pages, dealing with the list of subjective attributes, descriptions, and rating scales; and c) final page, for additional comments by the drivers.

on a significant number of vehicle set-ups and models can have significant positive impact on the design and development process, since, especially in the initial stages, it allows discarding design solutions that may not be appreciated by the customer, or shortening the design steps, e.g. by reducing or eliminating the final subjective assessment. To allow correlation, (i) the objective and subjective assessments of each ride comfort aspect must be performed through the same experimental tests; and (ii) specific attributes, rather than a

Table 4. Summary of correlations between objective metrics and subjective attributes obtained from the same manoeuvre [4], [7], [10], [64].

	Objective metric	Subjective attribute	Manoeuvre
Primary ride	$RMS\left(\ddot{\theta}\right)$	Isolation from road inputs: pitch control	Flat roads Uneven roads
	$t_{Settling,\ddot{\theta}}$ $P2P\left(\ddot{\theta}\right)$ $RMS\left(\ddot{\theta}\right)$	Pitch under braking/acceleration	Acceleration and braking
	$RMS\left(\ddot{z}_s\right)$	Isolation from road inputs: vertical ride control or bounce	Uneven roads: bumpy roads with high wavelengths
	$RMS\left(\ddot{\theta}\right)$	Isolation from road inputs: pitch control	Uneven roads: bumpy roads with high wavelengths
	$RMS\left(\ddot{\phi}\right)$	Isolation from road inputs: road copying	Uneven roads: bumpy roads with high wavelengths
Secondary ride	$RMS\left(\ddot{z}_{Seat}\right)$	Bobbing vibrations or choppiness	Flat roads
	$RMS\left(\ddot{z}_{Seat}\right)$	Shake or choppy vibrations	Uneven roads: joinery of cement patches or small cracks
	$P2P\left(\ddot{z}_{Seat}\right)$	Small impact	Bump
	$RMS\left(\ddot{z}_{Seat}\right)$		Cleat
	$P2P\left(\ddot{z}_{Seat}\right)$	Large impact	Bump
	$RMS\left(\ddot{z}_{Seat}\right)$		Cleat
Road holding	$t_{Settling,F_z}$ $RMS(F_z)$	Disturbance dissipation	Cleat

generic score on the subjective comfort level, must be assigned to the different ride quality aspects.

Based on the synthesis of the information from the references of this section and the industrial procedures to which the authors have been exposed, the correlation process can be split up into four phases, according to Figure 10. The first step, see Phase 1 in the workflow schematic, involves data gathering in terms of subjective scores and objective metrics for different vehicle configurations, i.e. several vehicle models (e.g. a case study vehicle prototype under development, and multiple benchmarking production vehicles of other car makers), or various suspension tuning settings for the same vehicle. Phase 2 involves the a priori association among the objective metrics, the most relevant subjective attributes, and manoeuvres, based on the correlation experience deriving from previous analyses. The pairing procedure simplifies the following data analysis steps of the process, since only specific and meaningful attributes will be correlated to each metric, for specific operating conditions. In some cases, e.g. [7], [10], [64], [70], the pairing is implemented before the experiments, and therefore can enable a reduction of the tests for which the subjective assessment is required. Table 4 provides a summary of the pairings from the literature.

Once the evaluation metrics have been collected and paired, the correlation process, corresponding to Phase 3, can be carried out. Linear correlation, see the theory in [71], is the most widely used method to observe the direction and strength of the relationship between the objective metrics and subjective scores. The coefficient that expresses the level of linear correlation is called Pearson product-moment correlation coefficient [71], R_P, and is defined as:

$$R_P = \frac{n\left(\sum_{i=1}^{n} x_i y_i\right) - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sqrt{\left[n\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i\right)^2\right]\left[n\left(\sum_{i=1}^{n} y_i^2\right) - \left(\sum_{i=1}^{n} y_i\right)^2\right]}} \tag{3}$$

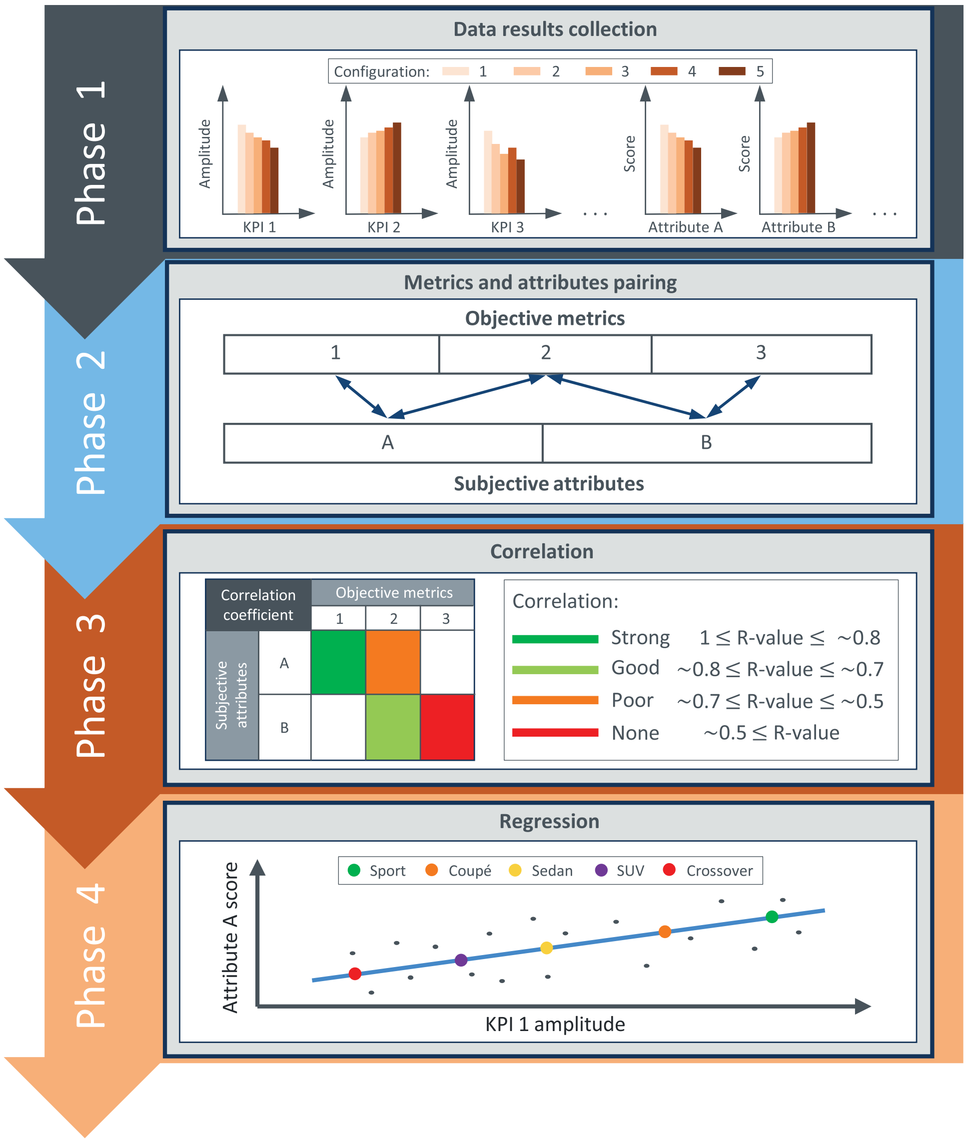


Figure 10. Schematic of the workflow of the subjective-objective correlation process.

In (3), n is the total number of data pairs, x is the independent variable, and y is the dependent variable. Typically, the objective metric is assumed to be the independent variable, while the rating of the subjective attribute is the dependent variable, since the ultimate goal of the correlation is to predict the subjective attributes from the objective metrics.

Instead of the Pearson linear correlation coefficient, Ali Böke et al. [16] use another type of correlation coefficient, the so-called Spearman coefficient, R_S:

$$R_S = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{4}$$

where $\bar{x}$ and $\bar{y}$ are the sample means of the independent and dependent variables, respectively. While the Pearson coefficient defines a correlation between the two variables through a linear law, the Spearman coefficient indicates whether the two variables are correlated by a generic monotonic function. Interestingly, in the available literature, all authors end up considering the case of linear relationship between the variables. In fact, also Ali Böke et al. [16] find a linear regression function, after identifying the correlation through R_S.

R_P and R_S are also simply called R-values, and are positive or negative scalars that vary between – 1 and 1, where an absolute value of 1 corresponds to a strong correlation between two variables. A positive R-value means that by increasing the independent variable, the dependent variable also increases, and, in the case of the Pearson coefficient, the increment is linear. Vice versa, a negative R-value implies a decrease of the dependent variable for an increase of the independent variable. An R-value magnitude exceeding ~ 0.8 indicates a strong correlation between the variables; the ranges from ~ 0.7 to ~ 0.8 and from ~ 0.5 to ~ 0.7 correspond to good and poor correlation, respectively; finally, values below ~ 0.5 are symptomatic of absence of correlation [4].

If a strong or good correlation is detected, Phase 4 of the process can be implemented. Linear regression is the most common method to describe how the rating of a subjective attribute varies as a function of changes in the correlated objective metric. The target is to find the y-intercept a and the slope b of the line that minimises the sum of the squares of the vertical distances from each data point to the line itself, which is achieved through:

$$y = a + bx \tag{5}$$

$$a = \frac{\left(\sum_{i=1}^{n} y_i\right)\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} x_i y_i\right)}{n\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i\right)^2} \tag{6}$$

$$b = \frac{n\left(\sum_{i=1}^{n} x_i y_i\right) - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{n\left(\sum_{i=1}^{n} x_i^2\right) - \left(\sum_{i=1}^{n} x_i\right)^2} \tag{7}$$

A further indicator of a good correlation between the variables is the coefficient of determination, R^2:

$$R^2 = \frac{\sum_{i=1}^{n}(y_i' - \bar{y})}{\sum_{i=1}^{n}(y_i - y_i')} = R_P^2 \tag{8}$$

where y_i' is the predicted value – computed through (5) – for a given x_i. This coefficient is the amount of variation in the dependent variable that the regression line and the independent variable can explain [71]. The result means that the percentage of variation in the dependent variable is accounted for by the variation in the independent variable. Only correlation results with a coefficient of determination $R^2 \geq 0.6$ are considered in the literature.

Another possibility is to correlate more than one objective metric with a subjective attribute, by performing a multiple regression [70], which is defined by [71]:

$$y = a_{MR} + b_1 x_1 + b_2 x_2 + \ldots + b_k x_k \tag{9}$$

where x_l, with $l = 1,.., k$, are the independent variables; a_{MR} is the intercept with the y-axis (e.g. with two independent variables, (9) represents a plane); and b_l are the partial regression coefficients.

Figure 11 depicts representative examples of linear correlation results from the literature, with values of the coefficients of determination exceeding 0.9, with a) – d) referring to 50 km real road tests carried out by two vehicles, each of them assessed in two payload conditions; e) – g) to speed bump tests for different vehicles; and h) to asymmetric road excitation tests for different damper settings applied to the same car. The results allow to predict how a subjective score can change in response to variations of the objective metrics.

After conducting the correlation and regression to find a law relating the two considered variables, Lu et al. [70] perform a further step, namely the validation of the correlation, which consists in verifying that very similar correlation levels occur in various case study vehicles belonging to different segments, such as sedans and sport-utility vehicles. In fact, for simplifying the ride comfort design process, the subjective-objective correlations need to be valid for as wide as possible vehicle ranges.

Based on their correlation studies, Ali Böke et al. [16] have implemented a software tool that allows to predict the subjective SAE score [68,69] of a vehicle. The prediction is based on preliminary information to be provided to the tool, such as the type of manoeuvre, and the main vehicle parameters such as mass, front-to-total weight distribution, wheelbase, track widths, maximum vehicle width, centre of gravity position, tyre type and dimensions, suspension parameters, engine type, and driveline architecture. The ultimate goal – to be achieved through future developments – is to predict the influence of different vehicle parameters on the SAE score in the early design phases, without having to involve any human subjects.

From a different yet promising perspective, given the recent trends in machine learning applied to engineering design problems, Cieslak et al. [52] use a neural network approach to predict the subjective ratings. The study explores the effect on prediction accuracy of the main neural network parameters, including training algorithms (e.g. Levenberg-Marquardt and scaled conjugate gradient approaches), training functions (i.e. the functions to compute the training errors), activation functions, and hidden layer sizes. Additionally, overtraining prevention methods, such as noise injection, are implemented, to provide robustness and independence from the specific data sets. Despite the very relevant and promising analyses, the conclusions of [52] highlight the proof-of-concept nature of the study, which should be the subject of further work, to make machine learning approaches a viable – and possibly more effective and flexible – alternative to the traditional linear regression methods.

5. Conclusions and future developments

Vehicle ride quality assessment is an area in which car manufacturers and their suppliers tend to provide either obscure or incomplete information, given that it covers topics that are at the core of the internal – and often confidential – know-how of the respective company. Moreover, although a broad academic and technical literature, including a few reviews focused on the objective evaluation procedures, deals with road vehicle ride comfort aspects, there is not a systematic analysis of the correlation methodologies between the objective and subjective evaluation of ride quality. This survey has reviewed the relevant literature, and, by combining it with the industrial ride evaluation experience of the authors in high-performance passenger cars, has targeted the identified gap, by analysing:

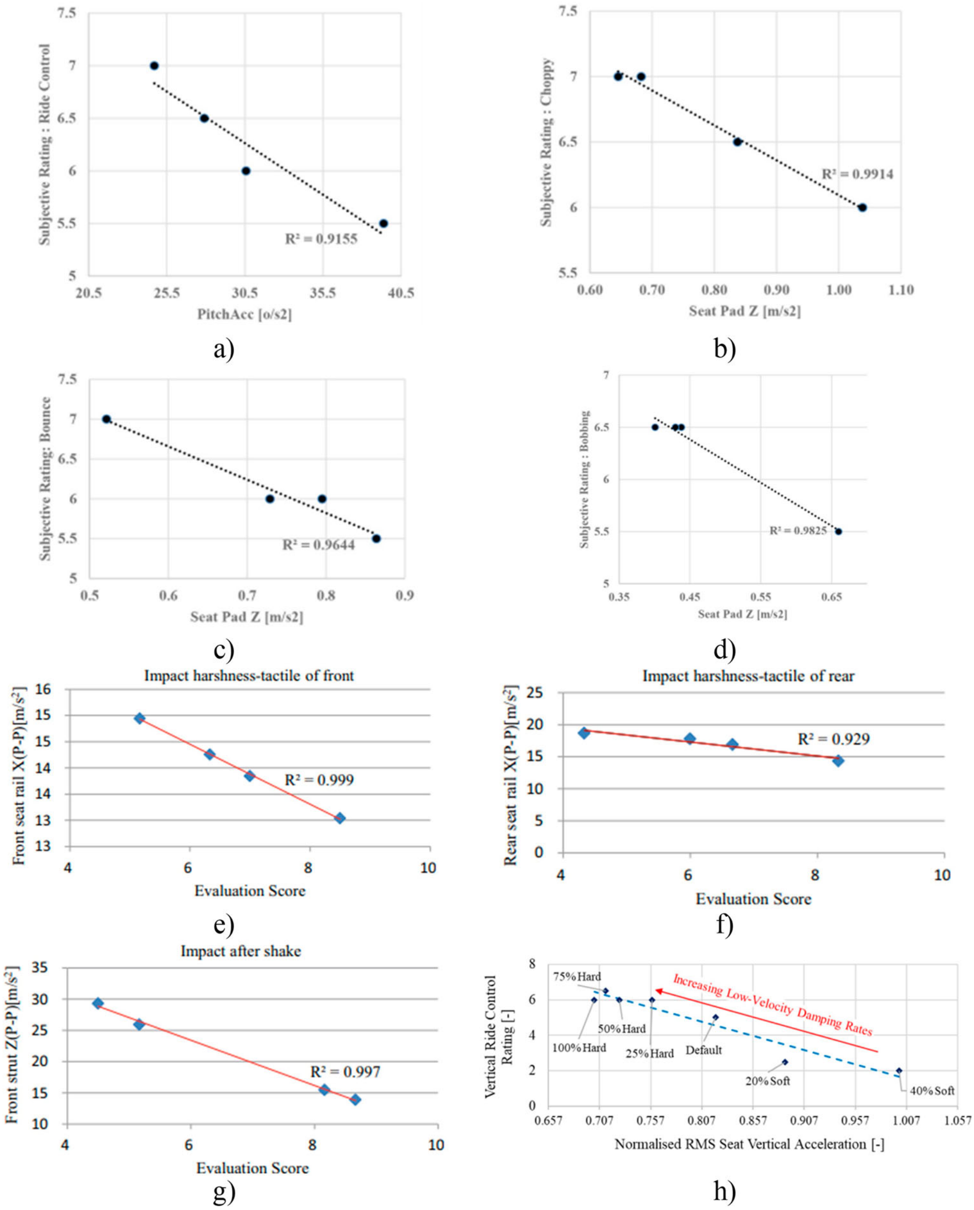


Figure 11. Examples of linear regression results from the literature. Correlations between: a) *RMS* pitch acceleration and ride control, referring to a 50 km road test, for two different vehicles in unladen and laden conditions (from [7]); b) *RMS* vertical acceleration of the seat pad and choppy vibration level, from [7]; c) *RMS* vertical acceleration of the seat pad and bounce control, from [7]; d) *RMS* vertical acceleration of the seat pad and bobbing vibration, from [7]; e) *P2P* longitudinal acceleration of the front seat rail and impact harshness (corresponding to the impact response indicators in Section 4), for a speed bump at 30 km/h, for different vehicles (from [70]); f) *P2P* longitudinal acceleration of the rear seat rail and impact harshness, in the same conditions as for subplot e), from [70]; g) *P2P* vertical acceleration of the front suspension strut and impact after shake (which can be considered equivalent to the disturbance dissipation attribute in Section 4), in the same conditions as for subplot e), from [70]; and h) *NRMS* vertical acceleration of the seat and vertical ride control, for a straight line test on an asymmetric road profile exciting chassis twisting, for different damping rates of the shock absorbers (from [4]).

- The key elements of the objective evaluation process, namely: (i) the key performance indicators, including their relevance to either ride comfort or road holding, and their association to specific manoeuvres; (ii) the ride evaluation manoeuvres, which can be divided into single obstacle and long-type road based tests, depending on the road profiles; (iii) the instrumentation, providing the data for the computation of the metrics, and typically including accelerometers on both the vehicle body and unsprung masses, as well as on the human machine interfaces (physical points of contact), e.g. the seat and pedals; potentiometers to measure suspension stroke; and 6DoF inertial measurement units installed on the sprung mass; and (iv) the methodology to obtain the data, which can involve using real vehicles either driven on dedicated test tracks or operating on post-rigs, or, alternatively, adopting high-fidelity driving simulators or simulation models.
- The main components of the subjective evaluation methods, i.e.: (i) the subjective attributes, qualitatively describing specific and relevant aspects of the ride quality, for which a classification has been proposed, given the very broad range of available definitions from different sources; (ii) the procedures to be followed by the involved test drivers/passengers, including detailed evaluation questionnaires; and (iii) the appropriate selection of the human evaluator sample and control of the test conditions, to reduce or predict/control the inevitable variability of the subjective scores, e.g. related to the level of driver experience, anthropological factors, and environment.
- The typical steps to establish the correlation between the objective and subjective ride assessment results, including: (i) data collection; (ii) pairing the objective metrics with the subjective attributes; (iii) calculating the correlation levels; and (iv) obtaining the regression coefficients and related – usually linear – functions, with the ultimate target of predicting the subjective scores only from the objective metrics, without having to repeat the subjective assessment for each new vehicle design. To maximise and generalise the benefit on the ride design process, the strength of the correlation identified through (i) – (iv) should be verified across multiple vehicles of different segments.

In summary, the correlation between objective indicators and subjective attributes could lead to significant time and cost savings in the vehicle development process, by a priori discarding design choices, such as suspension geometries and tyre selections, which could have a negative impact on customers' satisfaction. However, to reach such benefits, further research is required, with focus on: (i) establishing the required tools for dealing with nonlinear correlations, rather than conventional linear regressions; (ii) integrating the most recent machine learning methodologies into the correlation process, to establish complex multi-variable models of the subjective human ride sensitivity; and (iii) developing and comprehensively assessing tools to automatically and robustly translate the vehicle measurements into subjective scores, and vice versa.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Patrick Gruber http://orcid.org/0000-0003-1030-6655
Aldo Sorniotti http://orcid.org/0000-0002-4848-058X

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