18
VEHICLE FUNCTIONS

18.1 SYSTEM DESIGN

The goal of a system approach to vehicle design is to define the technical specifications of each component, in such a way that the vehicle, as a whole, performs its functions according to assigned procedures and objectives.

By technical specifications, we mean a set of physical measurements that define each part, completely without the use of detailed drawings.

The system approach to design allows project, even the most elaborate one, to be carried out by assigning activities to teams working in parallel, each with comprehensible objectives that can be checked autonomously, and finalized to the overall performance of the vehicle. The system approach also allows a project to be developed, using standard components produced by suppliers, these components being developed for the purpose or chosen from a catalogue.

Finally, the system design is the initial phase of each project, when the feasibility of reaching the assigned targets is verified; this phase is usually called a *feasibility study*. The technical specifications of the main components are part of the concept documentation.

In the continuation of this section we will try to explain how to assign and measure overall vehicle performance and functions.

Unfortunately, performance and functions cannot be defined absolutely, because they are conditioned by the customer's expectations of the product he will buy, and these expectations depend on both objective and subjective parameters. Nor would we forget that these expectations are conditioned by product alternatives existing on the market when the product will be sold, alternatives which are usually unknown when the project is launched.

G. Genta, L. Morello, *The Automotive Chassis, Volume 2: System Design*,
Mechanical Engineering Series,

Let us consider the climate system as an example.

Some functions of primary importance are easily identified.

We can assume that the objective of the climate system is to allow the passenger compartment to reach the assigned comfort temperature in a given time, notwithstanding the existing outside temperature. In reality, this time (cool-down or warm-up time) is only an approximate parameter; we would not want ideal comfort temperatures to be reached too quickly, causing passenger discomfort due to too strong a flow of air on the skin or high temperature gradients in the air.

Heat flux on passengers appears to be a matter of judgement, further complicating our understanding of the phenomenon.

In a luxury car, it might be mandatory to obtain comfort conditions automatically, requiring the passenger to adjust temperature control only. A few years ago it would have been a wild guess to design a multi-zone climate system for medium or small cars. Nevertheless this feature is beginning to appear in these cars and could became standard in the near future; when such system were designed, they may have seemed waste of time and money.

On next generation medium cars, automatic outside odor abatement could become indispensable. The abatement efficiency of various odorous reference substances should therefore be defined and measured.

In this connection, it should be remembered that too ambitious a specification could increase the product cost in ways that could prove to be unrecoverable in the final price.

Likewise, there are other functions that, although of secondary importance, cannot be neglected and, sometimes, impact other systems. They could be designed, for example, with goals like these:

- to reduce fuel consumption due to the climate system to a minimum;
- to reduce to a minimum the power required to the engine, especially during sudden acceleration;
- to minimize the noise of air flux into the passenger compartment;
- to control humidity, so as not to fog the windshield or side windows, etc.

Thus we see that in an apparently simple case, it can be very difficult to identify functions and specifications and that this identification should be done only after a careful study of customer expectations, which are in part a priori and in part depend on the competitor's products.

It is also difficult to define the boundaries of the climate system, or to identify which components influence the climate system by their behavior.

As a matter of fact, in a traditional approach, the climate system would be limited to:

- the heat exchange group, including the heater and the evaporator, the air channels and nozzles that direct the conditioned air to the passenger compartment, a part of the body system;

- the compressor, a part of the engine system;
- the electronic control box, a part of the electric system.

But, if we try to improve our control over climate system functions, this list should be expanded to include, for example, windows and windshield, responsible for an important part of the radiated heat; door panels, responsible for part of the transmitted heat; seats, as they influence human body heat exchange; and gearbox transmission ratios for their influence on engine warm-up.

The boundaries of the technical specification influencing certain function are wide and exceed the boundaries of the components dedicated to this function.

We suggest that a correct approach to system design should include, at least, the following steps.

1. To define the functions performed by the system.
2. To define the parameters that best measure those functions and the target values they should reach to obtain customer satisfaction.
3. To define which components are part of the system, because they influence the achievement of the target values.
4. To identify other system functions, if any, in competition with those of point 1.
5. For each component, to establish a set of technical specifications coherent with the system function target values.

Therefore system engineering implies the study of components that are normally classified under different automotive engineering disciplines; in the example of the climate system, we find components that are part of the body, the powertrain and of the electric system; these components are usually located in different sub-assemblies of the car.

The chassis system design we will study in this book is similar. We will study, for example, dynamic performance; a major factor here is the car's top speed. For a correct system approach, we will study not only the transmission as a component of the chassis, but also engine specifications (part of the powertrain), and aerodynamic resistance (part of the body system).

If engineering subjects are, by their nature, interdisciplinary, system engineering must likewise exceed the boundaries of its individual subjects.

A traditional, topological approach, on the other hand, classifies and studies vehicles according to three main subsystems.

- The chassis, as the cluster of components dedicated to vehicle path control, such as transmission, suspension, brakes, wheels and steering mechanism, with their dedicated supporting structures.
- The powertrain, as the cluster of components dedicated to traction power generation, such as engine, fuel supply, intake and exhaust plants.

- The body, as the structure supporting all other components including the passenger and payload compartment.

This book, dedicated to chassis system design, will consider all those functions that are primary to the chassis; nevertheless, while studying a function such as dynamic performance, we will also consider some aspects of the engine and the body or, in terms of automatic system controls, we will consider some issues interfacing with the electric and electronic system.

System design is necessarily rough, because it only studies the baseline specifications of the components included in the system; design details of the same components are left to specialists in each.

This approach will be useful not only to engineers, but to anyone involved in new vehicle development process.

18.1.1 Functions perceived by customers

Let us consider all functions performed by the vehicle, with particular reference to automobiles.

Vehicle functions can be defined as the categories by which the customer rates vehicle performance.

A complete list of functions, probably to be expanded in the future, can include the following:

- Appearance.
- Available space.
- Ergonomics.
- Climate comfort.
- Dynamic comfort.
- Dynamic performance.
- Handling.
- Safety.
- Resistance to age.

Each function can be explained through a certain set of requirements, which are qualitative and quantitative attributes that the vehicle must possess to perform each function correctly; we will describe these requirements shortly.

The first listed function (this list is not ranked by priority) is *appearance*, the ability to appeal to the customer; even if we these are beyond our scope, we will say the pertinent requirements involve the body, in terms of shape, volume, materials and details.

The contribution of the chassis to this function is marginal but not negligible and includes tire and wheel size, a part of car appearance; the engine also gives contributes through its proper lay-out at open hood, or through hood shapes and ventilation openings.

Roominess, or, from a designer point of view, the use of space, is important, because it embodies the primary objective of carrying people and goods.

Customers don't expect unlimited room, depending the class of the car, they are interested in; what is important is how much limited space can be rationally used. The room expended on car components is unavailable for this use; component lay-out should be designed to limit as much as possible any intrusion into the passenger compartment. This explains why we spent so much time on transmission and suspension bulk in the first volume.

Other important requirements also hinge on body design, such as roominess and availability of space to organize small objects; another important requirement is adaptability (tilting or removable seats), in order to enable the customer to change the car interior to suit different transportation needs.

Car *ergonomics* can be defined as the ability to minimize the physical activity required by a given operation while using the car. Within this function, we usually include the pleasure of driving the car, including the many sensations the customer feels while driving.

The requirements of this function again involve the car body and include:

- the ease of entering and exiting the car for driver and passengers, of opening and closing doors, the glove compartment, hood, trunk, etc.;
- the ease of identifying and reaching the most important controls with minimal reach;
- the comfort of the driver's posture;
- the ease of loading and unloading the transported goods.

Chassis design is primarily affected by the requirements established for car controls such as the steering wheel, gear shift stick, clutch and brake pedals; these have to do with their operating force, the placement of the controls and the feeling perceived by their operation. Any control, in fact, not only receives an input that should be minimally tiring, but returns a feed-back that should inform the driver about the correct accomplishment of the maneuvers.

We commented about *climate comfort* in our example. In this case, as well the related requirements affect body design and, partially, the engine.

The *dynamic comfort* function is evaluated by the ability to suppress all acoustic and vibration nuisances from outside (road pavement and other vehicles) and from inside (engine operation and component vibration).

The related requirements involve almost all vehicle components, as they participate as sources and potential transmitters of such disturbances.

Noise and vibration contain information useful for both driver and passengers. A totally silent vehicle, without vibrations, could prove to be dangerous, as has been demonstrated by experience with active noise suppression. In addition, some noise is peculiar to particular types of car, as, for example, sports cars.

The target is not total suppression but an acoustic environment compliant with customer expectations.

Filtering of components vibration is a task usually assigned to the body system, while filtering noise and vibrations from the road is usually assigned to the wheels and suspension.

Filtering powertrain noise (engine operation) involves powertrain suspension and the intake and exhaust system.

Unbalance specifications are assigned to any potential source of vibration.

The *dynamic performance* function includes requirements that are easy to measure, such as top speed, gradeability, acceleration and pick-up. Requirements that are more difficult to evaluate meaningfully are drivability and fuel economy.

Requirements involve all chassis components from the engine to the body and, in general, the entire vehicle.

Handling functions are usually defined as the vehicle's ability to follow driver inputs on the controls, when modifying car speed or trajectory; these controls include separate or combined operations on the steering wheel, brakes and accelerator.

Handling function requirements involve not only suspension, tires, steering mechanism and brakes, but also engine and transmission. Overall properties of inertia (mass and momentum) have vital importance for this function.

The *safety* function is usually classified in three ways:

1. *preventive safety*, such as the ability of the vehicle to keep the driver constantly updated on corrective maneuvers to be undertaken; a typical example of this category includes not only outside visibility, visibility of the main instruments (i.e. speedometer, outside thermometer, etc.) but also car trim variations;

2. *active safety*, such as the ability of the vehicle to react to driver inputs with a response that should be immediate, stable and proportional to the action, while avoiding obstacles or dangerous situations;

3. *passive safety*, such as the ability to limit, when a collision is unavoidable, the severity of injuries to car occupants, to pedestrians or to passengers of other cars, involved in the collision.

Safety cannot be, by definition, total, but requirements should be established for the most statistically relevant situations; homologation requirements are an important part of this approach, together with manufacturer's technical policies. In the passive safety category, repair cost limitations following low speed collisions have been added recently.

Safety involves all main vehicle components; the body is particularly involved in preventive (inside and outside visibility, lights) and passive safety (structures, passive and active restraint systems, component lay-out, surface materials and finishing).

The chassis must comply with all active safety requirements for suspension, brakes and tires, and with passive safety requirements, such as intrusion into the passenger compartment following a collisions.

The engine system is involved in passive safety as far as fuel spills after crashes and consequent fire hazards are concerned.

The *aging resistance* function is the ability of vehicle system and components to maintain their functions unchanged or to limit their degradation with aging within acceptable limits; reliability is a requirement of this function. Aging resistance involves all vehicle components and, obviously, all chassis components.

18.1.2 Technical specifications

Each vehicle function can be described through a coherent set of measurable requirements; compliance with them guarantees customer satisfaction with the vehicle.

These requirements determine the technical specifications of all components.

Each part or subassembly could be fully defined by an engineering drawing, containing all relevant geometric dimensions and materials. In reality, the detailed knowledge of complex components is irrelevant to the car manufacturer, who is more interested in performance than specifications. A very detailed cannot always guarantee complete fulfillment of the desired performance. In many cases, car manufacturers lack the technical competencies to understand complex details.

Technical specifications solve this problem by providing global and synthetic information only; it is therefore necessary to establish, for a certain component, what is relevant for system function. A technical specification should list:

- what physical properties describe the requirements requested for the component;
- in which conditions those properties must be measured;
- what values (with allowed tolerance) they must assume to obtain the desired system performance.

These technical specifications, together with simple outline drawings, represent the only technical documentation useful for managing the relationship between car and component manufacturer.

The component manufacturer's point of view is necessarily different, since he must create technical documents to produce the needed part consistently. After all it isn't rare that some second tier supplier is producing other parts that will be integrated into the final subassembly. The first tier supplier must therefore use his technical specifications to advantage.

Consider the example of a tire.

The vehicle system utilizes the tire to express forces on the wheel along the three directions (vertical, longitudinal and transverse); tire technical specifications will examine these three parameters first.

A reasonable approach to tire specification might be to determine maximum allowed values for these directions and magic formulae coefficients; their values can be calculated by mathematical models directly or interpreted by these models as applied to satisfactory results of experiments performed on the car.

Other specifications could describe the tire's age resistance, with acceptable values of tread wear using certain mission as reference.

The figures of vertical elasticity and damping close this specification list.

The common characteristics of these parameters are:

- they must be correlated with the function we wish to obtain on the vehicle;

- they must be overseen by the supplier, since he is the manufacturer, without implying a detailed knowledge of the application.

Other characteristics, such as, for example, the chemical composition of cord fibers applied to the tread, are not generally involved in vehicle operation and, if they are, the link between chemical composition and system behavior is part of the proprietary know-how of the supplier.

Technical specifications, therefore, define the performance that we want to obtain, but not the details that allow us to obtain this performance.

On the other hand, specifications should not be too superficial; for example, we should not make the mistake of providing a supplier specifications on road durability without referring to the driving conditions and the typical trip in question; a good specification should enable the supplier to evaluate for himself the results of his effort.

Continuing with the tire example, it is clear that the technical documents available to the supplier will be much more detailed than those used by the car manufacturer as technical specifications; the supplier will have available a complete set of drawings of the tread, including detailed dimensions, cord texture, materials, fixtures and production set up, etc. The design tools of the supplier will be able to correlate these parameters with tire performance on the vehicle system which are almost coincident with the technical specifications.

Some details, such as wires included in the body - whose performance is not only dependent on reference dimensions (diameter) but also on the manufacturing process in the steel mill - should be described by specifications including only diameter, yield and the physical properties of their surface.

Technical specifications represent a universal simplified language, allowing such different industrial organizations as final manufacturer and supplier to cooperate in reaching the same objective, the final customer satisfaction.

The same logic can be usefully applied within a company, particularly a vehicle manufacturer, to integrate the activities of different departments.

Although there is no conceptual obstacle to developing each component from scratch, it is always useful, before taking this decision, to clarify which function the component performs on the vehicle, how it can be quantified, and from which values the objective of satisfying the customer is obtained.

In this way it is possible to manage, with relative simplicity, complex activities involving a number of people, braking down each objective into subobjectives that are measurable and understandable by the different parties involved.

18.1.3 Chassis system design

We have seen that the automotive chassis contributes to the following vehicle functions:

- dynamic performance;
- handling;
- ride and acoustic comfort;
- ergonomics;
- safety.

The engine and transmission relate to dynamic performance, in terms of available power; the body (aerodynamic resistance), tires (rolling resistance), transmission (mechanical efficiency) and mass properties of the vehicle involve dynamic performance in terms of absorbed power.

Handling and active safety are influenced by suspension and steering system geometry, by brake design and by the elastic properties of tires; the transmission determines the interaction between cornering and traction forces. Chassis control systems play a fundamental role.

Ride comfort is influenced by disturbances, essentially vibrations, coming from tire-ground contact and is affected by suspension geometry, by the elastic and damping properties of springs, bushings and shock absorbers, and by the vertical properties of tires.

Acoustic comfort, on the other hand, requires a notable development of our knowledge of body structure and trim. For this reason, this function is usually studied in body design.

As far as controls are concerned, ergonomics involves chassis design: the steering system, brake and transmission (clutch and shift stick); control systems contribute to this function through power assistance and automatic transmissions.

Passive safety involves chassis design and component intrusion into the passenger compartment and structure; since most cars have a body that includes in a single shell both chassis and body structures, we generally study this function as part of body design.

The objective of the design methods explained in this book dedicated to chassis design is therefore to design chassis components that satisfy the above functions at the vehicle system level.

The adequacy of these methods might appear at least partially unsatisfying, because we will explain how to verify which function an assigned vehicle is able to perform; we will also identify which components condition those functions but not how these components must be specified in order to perform the functions at the desired level. We are able to tackle this problem only *a posteriori*, while an *a priori* approach would be desirable.

This qualification could apply to all design courses, because if designing means to define a product that does not yet exist, what is really taught is to verify whether an already defined product is able to perform an assigned function.

The designer's job is, therefore, to assume an hypothesis and to verify the results that can be achieved; a deviation from the objective will guide to define a different hypothesis that will again be verified. The designer will be more efficient, if the first approximation hypothesis is close to correct, but, in any case, design will remain a trial and error process.

A technical specification definition is further complicated by the fact that the final judgement on the product will be issued by the customer and not by the designer, and customer judgments are sometimes difficult to express concretely, because they are influenced by unmeasurable parameters and alternative offers on the market that may be unknown at the beginning of the development process.

Technical specifications are developed and determined through different strategies, according to a process that can be divided into two parts, called *target setting* and *target deployment*. The target setting phase consists in setting objectives for each of the functions perceived by the customer; this job will be more fruitful if subjective judgements are avoided and only objective measurements are used. If this requirement appears easy to be meet for functions like top speed, acceleration, and gradeability, it will be difficult for functions like handling, where subjective feelings come into play.

We will see in the following paragraphs how subjective feelings can be transformed into objective measurements.

In the next phase of target deployment, as a first step, vehicle subsystems according to function are identified and their specifications tentatively set; the specifications adequacy to the targets will be verified, correcting any errors in the specification.

These verifications may be performed using mathematical models of the vehicle and in some cases also by building and testing simplified prototypes (*mule cars*) that will allow complex subsystems to be verified.

18.2 OBJECTIVE REQUIREMENTS

If we want to define vehicle functions and, particularly, measure the main requirements that determine those functions, we must refer to the test procedures used for this purpose; vehicle objectives are, in fact, set with reference to those procedures.

We commonly identify *objective* and *subjective* requirements. The first ones are directly measurable with the instruments of classic physics; the second are determined only by the satisfaction of the final vehicle user, but they can be converted into objective measurements through statistical investigations of customer groups.

A classic example of an objective target might be the time to accelerate the vehicle in top gear from one speed to a higher one. This is easily measurable, when reference conditions (road grade, wind speed, atmospheric pressure, etc.) and load conditions are set. This test can be performed by a professional driver who is able to achieve repeatable results; each test, even a simple one, is influenced by driving behavior.

If we want to define the customer satisfaction level, we should ask ourselves how it can be measured and if it depends on this requirement only; if that is the case, satisfaction will be influenced by the customer's expectations, depending on the class of the car, driving habits, etc.

The required objective follows from a statistical study of the reaction of a group of customers driving this car; the study of customer satisfaction on different questionnaires leads to significant data derived from subjective measurements. The customer sample must include only people likely to be final customers of the car under development.

We will refer in this paragraph only to objective measurements of vehicle performance involving the chassis, which are, as we have seen:

- dynamic performance;
- handling and active safety;
- ride comfort;
- ergonomics;
- passive safety.

For each of these we will comment on test procedures and measurable data; we will consider passive safety only when speaking about regulations.

18.2.1 Dynamic performance

For this kind of test it is necessary, for safety reasons, to use test tracks closed to public traffic.

Speed and acceleration tests should be performed on a flat straight road that is long enough to accomplish all tests reliably; a launch ramp should also be available that allows the vehicle to reach top speed before its measurement.

Sufficiently long constant slope roads, at different inclination angles, should be available for gradeability tests.

Loop tracks can be used to imitate of road trips that are particularly significant for vehicle use; according to the know how of each manufacturer, these tracks allow, while driving following certain rules, the measurement of average speeds and fuel consumption comparable to real values.

Because engine performance is influenced by air density and humidity, climate conditions during such tests are significant; a suitable condition is an outside temperature in the range between 10÷30°C, with no wind and rain.

As an alternative to the test track, subject to variable climate conditions and, therefore, not always available, roller benches can be used, allowing electric brakes with electronic control to simulate vehicle driving resistance on the road; in this case, the car is driven according to an assigned speed time history. This practice is particularly useful for measuring fuel consumption.

A roller bench, when contained in pressure and temperature controlled chamber, allows dynamic performance at temperature and altitude conditions different from those available outside to be measured.

Test vehicles must be driven for a certain distance (about 5,000 km) after assembly to stabilize mechanical frictions and tire rolling resistance, since these parameters are subject to a certain settling depending on surface wear.

Since performance also depends on transported weight, it is necessary to control this value within a statistically meaningful tolerance; usually 2 passengers (including driver) and 20 kg of baggage are used for testing. For industrial and commercial vehicles the full load condition is considered.

The instruments used in these tests are quite simple, as far as speeds are concerned: they include optical devices to actuate stop watches that measure driving times, while space driven is determined by the position of these devices along the track.

Fuel consumption is measured by volumetric flow meters on the engine feed pipeline; in this case the recycled flow to the fuel reservoir must also be taken into account; sometimes an auxiliary tank is applied that is weighted before and after the test.

The best known dynamic performance is *top speed*, which is the maximum vehicle speed on a flat road, after a reasonably long launch ramp.

Acceleration is usually defined as the time necessary to reach a predetermined speed (usually 100 km/h or 60 mph), starting from a still condition, using the gearbox, at full throttle; sometimes it is also measured as the time necessary to cover a fixed distance (usually 1 km or $\frac{1}{4}$ mile), starting from a still position, using the gearbox, at full throttle. This kind of test must be repeated on a manual gearbox a number of times, to allow the driver to identify the best strategy to working the controls, because start-up and shift times influence the final result.

By contrast, *pick-up* time is instead the time needed to increase the vehicle speed, starting from an initial fixed value, without using the shift stick but at full throttle. The initial speed can be 50, 60, 70, or 80 km/h, while the final one is usually 100 km/h; the gear is usually the top one or, if different, the top speed gear. The distance driven could also be used to measure this performance.

Gradeability is the maximum road slope at which the vehicle is able to start up and be driven at constant speed, without slippage of the clutch; this value is approximated according to the available slopes on the test track. The grade is measured by the difference in elevation at the two end of the test track, divided by the horizontal projection of the track; this is the tangent of the longitudinal road inclination α.

Among the practices of manufacturers are reference loop drives on closed tracks or open roads which allow one to evaluate road performance under controlled conditions; in this case *average speed* or *driving time* are measured.

Increasingly congested traffic conditions have distracted customer attention from the performance obtained by intensive gearbox use, putting emphasis instead on pick-up time at low speed; the most recent statistical surveys correlating subjective judgements of performance, favor this measure on short test distances.

This trend increases the importance of low speed (1,500÷2,500 rpm) engine torque, with reference to maximum power. It is therefore not inaccurate to include *drivability* in the category of vehicle dynamic performance.

Drivability can be defined as the vehicle's ability to increase or decrease its traction force quickly, without fluctuation around the final desired value.

At the beginning of the test, the throttle pedal is depressed or released starting from a condition corresponding to the initial steady state reference speed.

Drivability is evaluated by examining the resulting car speed diagram as a function of time after the input time on the accelerator pedal, or by measuring the longitudinal vehicle acceleration. An objective evaluation parameter can be the number of peaks of this diagram before the asymptotic value.

Vehicle drivability is not only influenced by engine torque oscillations, induced by flow transients into the intake and exhaust ducts, but also by the elastic torsional stiffness of the driveline, from clutch to tires, and by the elasticity of powertrain and car suspensions mounts.

Fuel consumption at constant speed is usually measured between 50 km/h and top speed; the test is performed in top gear or, if different, on the top speed gear; this test is quite simple, but has a very low correlation with practical vehicle use, where speed variations and engine idling periods are very frequent.

For this reason, tests are always completed with a measurement of a driving cycle; this test is usually performed on a roller bench, able to simulate driving trips of different kinds; an important cycle will be described in the chapter on regulations.

It is a good practice to measure consumption at ambient temperatures different from the reference condition (usually 20°C) if the car is to be sold in countries where this condition is not significant; in this case, the effect of a cold start must also be investigated. On the road consumption measurements can also be performed, if there is sufficient control over ambient conditions.

18.2.2 Handling and active safety

Handling tests do not differ significantly from active safety tests and are therefore described together. This kind of test introduces a specific difficulty because on-road maneuvers can be many and their number is increased if different road pavement and conditions are to be considered.

Many manufacturers have adopted similar elementary maneuvers and most of these have been standardized by the ISO. Standardization applies to the execution of the maneuver only and sets no reference values for the output values to be measured.

The test track, usually a flat square that can be flooded under controlled conditions, provides marked courses that cars must follow; in this way the consequences of mistakes are not burdensome.

Cars are often equipped with roll over protection provided by additional wheels that contact the ground at high roll angles.

Vehicle instruments must be sophisticated because they have to measure dynamic values for the vehicle; the essential ones include:

- lateral acceleration;
- yaw velocity;
- vehicle side slip angle;
- roll angle;
- vehicle speed.

For the definition of each see the fourth part of this volume.

A fixed reference system is necessary to establish these values through instruments installed on the vehicle; an inertial platform is therefore used that measures the six components of rotation and displacement of the vehicle sprung mass with reference to the ground.

In many tests a particular steering wheel able to measure steering angle and torque is used.

Tests are classified as *open loop* and *closed loop* , with reference to the role of the driver during the maneuvers. In the first case, the driver manipulates vehicle controls (steering wheel, brake and accelerator pedals) according to a preset procedure, regardless of the result; in the second case the driver uses the controls as needed and tries to obtain specified objective, as, for example, driving along a course at the highest possible speed.

The simplest open loop maneuver is the *steering pad* (ISO 4138), where the vehicle is driven around a circle at constant speed.

This is an open loop maneuver because the controls are blocked during the test period, to guarantee a steady state motion.

Three different methods are considered depending on the skill of the driver, that are substantially equivalent in result; these are:

- constant curvature radius,
- constant steering wheel angle,
- constant speed.

Since these are the three independent variables that define motion, their test results can determine the remaining variables.

A typical value for the curvature radius could be 40 or 100 m; it is important that tests are performed in such a way as to obtain different values of lateral acceleration, starting from a very low one, which is useful to measure the Ackermann steering wheel angle.

This test allows the evaluation of the steering index of the vehicle and the determination of roll angle as a function of lateral acceleration; a maximum allowed lateral acceleration can be identified by a series of attempts.

We refer again to the fourth part of this volume for a definition of the parameters involved in this test.

To evaluate vehicle stability while entering a curve and the steering wheel realignment when exiting it, the *lateral transient test* (ISO 7401) is usually applied.

The car is stabilized on a straight road at 100 km/h or, if desired, at different speeds; in the step input version, the steering wheel is suddenly turned to a preset value; to simplify the maneuver, a steering wheel stop is set at the desired angle.

Without changing the accelerator pedal position, the steering wheel is kept turned for a specified time.

Important evaluation parameters are the gradient of lateral acceleration and yaw speed as a function of the steering wheel angle, the delay time between steering wheel angle peak, and yaw speed peak and the presence of overshoots on the yaw speed diagram (yaw speed peak higher than asymptotic value).

A variant of this maneuver is the application of a sinusoidal steering wheel input applying, as input:

- random function,
- triangular function,
- sinusoidal function,

at different frequencies.

The complexity of this test is evident despite the schematic simplicity of this transient between straight and curved steady state motions.

The *accelerator pedal release* maneuver (ISO 9816) is studies vehicle behavior when the accelerator pedal is released, while driving on a curve; this maneuver simulates what could happen if a driver attempts to drive at too high a speed.

It is possible to test vehicle stability and measure deviation from the original path. This test can be performed at the end of the steering pad test.

Two different methods are available.

- At a constant course by stabilizing the vehicle on the assigned curvature radius before releasing the accelerator pedal; the steady state speed can be increased as needed to investigate the influence of lateral acceleration.
- At constant speed, stabilizing at a certain speed on decreasing curvature radii.

The test output displays the interaction between the steering index, a function of lateral acceleration, and the varying cornering stiffness of tires due to the instantaneous change of traction caused by braking. The engine shows a braking effect increasing with initial rotation speed: the transient is affected by the selected gear ratio.

During this open loop test the steering wheel must be locked.

The evaluation parameters are the same as in the previous test, where longitudinal acceleration has to be added; because the steering wheel is blocked, there will be a deviation from the initial course after accelerator release; cars are usually designed so as to close the path after the transient slightly, without sensible discontinuity from the initial trajectory.

Still in the area of stability, *the braking in a curve* test (ISO 7975) has been designed, to add the application of brakes to the above procedure. Also in this case steering wheel is again locked.

To the parameters of the previous test, braking fluid pressure is added and the deviation from the initial course could be significant; the test is performed at increasing longitudinal accelerations until one of the wheels is blocked or the ABS system has started to work.

An important open loop maneuver is the *steering wheel release* (ISO 17288); the purpose of this test is to establish the vehicle's ability to return to a straight path after a curve.

The vehicle is stabilized on a steering pad at 100 km/h; path curvature is chosen so as to maintain a lateral acceleration of about 1 ms^{-2} and the test is repeated for growing acceleration values. At the beginning of the maneuver the steering wheel is left free to turn under the action of the existing forces on the contact points of the tires. The accelerator pedal is kept where it was at the beginning of the test.

The usual path parameters and the actual steering angle are acquired. Since steering wheel and lateral acceleration must show damped oscillations from an initial value to zero, damping factors measured on time histories are assumed as evaluating factors of these transients.

Side wind sensitivity tests for cars (ISO 12021) and for industrial vehicles (ISO 14793) are also available; for these vehicles specific tests can be used to examine the effect of trailers.

All the elementary maneuvers we have considered, although very complicated, do not correspond to real driver behavior; they are, nevertheless, very useful for understanding the natural vehicle response before any correction by the driver has been applied.

The opinion of the people that have designed these tests is that the first part of any real maneuver is always of the open loop type; in fact, drivers apply an action on controls (steering wheel , accelerator and pedal brake) whose amplitude is suggested by the desired response; the amplitude has been learned on previous similar maneuvers.

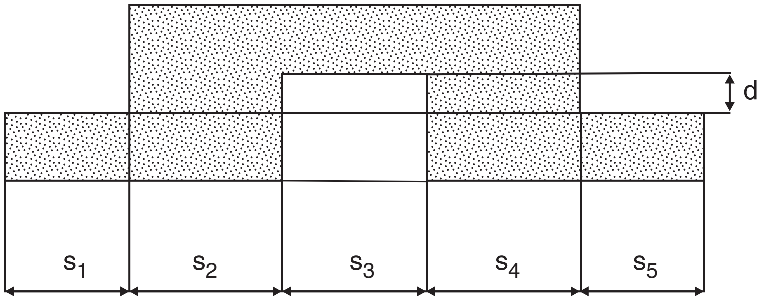

FIGURE 18.1. Course of a lane change maneuver, according to ISO 3888 standard.

After a short while corrections are applied, as soon as some deviation from expectation has been perceived. The simpler correction, the lower the deviation from the desired response.

A simple closed loop maneuver introduces difficulties in evaluation, as it depends on the different behavior or ability of different drivers.

The *lane change* maneuver (ISO 3888) studies vehicle stability by overtaking another vehicle or avoiding an obstacle; the relative course is shown in Fig. 18.1 and is driven from the left to the right.

The course is defined by rubber posts; the first stretch S_1 is the normal driving lane, the stretch S_3 represents the overtaking lane and S_5 again the normal driving lane.

The three stretches are joined by the zones S_2 and S_3; the right border of the overtaking lane is shifted by the deviation d to the left, with reference to the left border of the normal driving lane. The scheme of the course should be designed as follows (dimensions are in [m]).

Stretch S_1	length 12 m, width $l = 1,1\ w + 0,25$.
Stretch S_2	length 13,5 m.
Stretch S_3	length 11 m, width $l = w + 1$.
Stretch S_4	length 12,5 m.
Stretch S_5	length 12 m, width $l = 1,3\ w + 0,25$.
Deviation d	1 m.

Dimension w is the vehicle width, measured in [m] without taking into account side mirrors; the width of stretch S_3 cannot be less than 3 m.

This elementary maneuver is of the closed loop type, because driver course corrections are essential to avoid hitting any rubber post.

The car must be driven at 90 km/h in IVth gear and car speed should remain unchanged along the course; varying parameters may be used to compare different vehicles.

The maneuver is complicated and heavily influenced by driver skills; with professional drivers, interesting results can be gathered more by subjective impressions than objective measurements.

In order to assess vehicle stability while avoiding a sudden obstacle, the vehicle is tested many times on this course at increasing speeds; the vehicle enters stretch S_1 at the initial steady state speed, at which point the accelerator pedal is fully released to simulate obstacle detection. After repeated tests, the maximum obtained speed achieved without hitting any post may be taken as an objective evaluation of vehicle stability.

As far as the braking performance is concerned, the easiest repeatable test is to measure the stopping distance of the vehicle at maximum possible acceleration; if the ABS device is missing this test can identify the maximum possible deceleration without blocking any rear wheel.

It is useful to repeat this test on tracks with different levels of friction and with different vehicle load conditions; on low friction roads (for instance on icy roads) it is also a good practice to measure the vehicle path with different friction on the two sides of the vehicle (μ split). This maneuver, useful in evaluating ABS systems, simulates braking on a road with a wet or icy border.

The catalogue of maneuvers is not complete; many other tests are used to focus on specific problems.

18.2.3 Dynamic comfort

Comfort is correlated to passenger unease caused by vibrations between 1 and 100 Hz in frequency; higher frequency vibrations correlate solely with purely acoustic discomfort.

Vibrations in this range are caused by obstacles and hollows on the road surface, which are filtered by the elastic and damping properties of tires, suspensions and seats; these condition the influence of powertrain mass vibrations (caused by the road) and vibrations of the body, which enhance or reduce the effect of the road, according to their vibration modes.

Comfort tests are performed on closed tracks that reproduce the road surfaces the vehicle is most likely to encounter; the road must be maintained according to specific standards to allow repeatable results on these tests.

Ambient temperature must also be controlled and recorded because of its influence on the elastic and damping properties of elastomers, which are largely employed in the mechanical components connecting the ground profile with passengers; temperature also has a remarkable influence on oil viscosity of shock absorbers.

Measurements to be evaluated include the acceleration of the different parts in contact with the human body, such as floor, seat, steering wheel, etc.; other accelerometers could be set at different position in the mechanical chain, to monitor test accuracy and for diagnostic purposes.

It should be noticed that accelerations should be measured along the three main axes of the vehicle reference system, especially if the more important components are along the z and x axis. Vehicle speed measurement is also important, because it and the road profile validate the test.

Four profiles exist for elementary tests that replicate the most common road defects.

FIGURE 18.2. Typical defects of suburban and urban roads, relevant to vehicle comfort; at left a patched tarmac; at right a stone block pavement.

A motorway profile with perfect tarmac is characterized by a virtually flat surface, with peaks and hollows much further apart than the vehicle wheelbase; at speeds of 100÷120 km/h, this spacing may excite the natural vertical frequency of the powertrain and of the vehicle suspension. This kind of course is also used to identify and analyze vibrations coming from the shape of the tires and any defects in them.

A suburban road with a poor maintenance is characterized by hollows that are spaced closer than vehicle wheelbase, with different size pits, patches and ruptures of the wear layer; Fig 18.2, at the left supplies an example of these defects.

These kinds of defects involve a range of frequencies larger than the previous and excite the natural vibration modes of sprung and unsprung masses: comfort in this test is critical for customer satisfaction since these defects are widespread.

The stone block pavement (Fig. 18.2, at right) is still common in city centers because of its attractive appearance and relative immunity to ice damage; it is therefore a reference test for the urban environment and is associated with lower speeds than the previous tests.

Because of the nature of this surface the wave length spectrum is very wide, from a few centimeters to several meters. The consequent excitation encompasses the entire range of comfort frequencies, involving all suspension components and car structures.

The catalogue of comfort tests includes, usually, a single step obstacle, representing what happens when crossing a curb or a railway; this obstacle is represented by a steel bar of rectangular section across a flat tarmac road. This kind of obstacle generates a force pulse on the wheels and involves a wide range of frequencies, with vibrations along the z and x axis.

18.2.4 Ergonomics

Ergonomic functions involving the chassis are influenced by the position of controls and by the force required for their operation; the main controls include the steering wheel, brake and clutch pedals, gear shift stick and parking brake.

The current trend of widening the passenger compartment as much as possible makes the pedal board the starting point of preliminary studies of car habitability.

Installed into the passenger compartment, the pedal board is constrained by the following elements:

- front wheel well: its dimensions are determined by the front wheel steering envelope and by the suspension stroke; this volume should also take snow chains into account;

- the floor tunnel, for the transmission shaft on rear wheel driven cars and for the exhaust pipe in front wheel driven cars;

- the minimum clearance from the ground;

- the firewall, separating the passenger compartment from the engine, which is also used to attach the pedal board.

The most forward position possible for the pedal board is desired to increase the available space for driver and passengers. The limit to the front position is represented by the powertrain and by the steering box. The floor tunnel, from one side, and the wheel well, from the other side, limit lateral space for positioning the pedal board. These limits are especially critical on narrow cars.

The accelerator pedal is always in contact with the right foot of the driver, except when braking. It must be operated with minimal force and high precision: the foot requires a side rest to avoid interference from vertical vibrations.

The accelerator pedal stroke should be about 50÷60 mm.

The reference point for positioning the accelerator pedal is the most rearward position of the driver's foot when resting on the floor, according to the projected comfort angles. It is called the *heel point*.

To avoid excess contact between shoe and pedal, the relative motions of these two parts should be minimized.

Because of pedal motion, the shoe sole changes direction. Since the hinge point of the pedal is fixed, this condition of no slip between pedal and shoe can be obtained only in one position; it is preferred that this position be the one most frequently used, usually at mid stroke. The slip can be reduced in the other positions by curving the pedal.

The brake pedal can be operated by relevant forces and stroke precision is not very important.

According to regulatory standards, the control force must not be higher than 500 N, but it is suggested that this control be designed to limit the maximum pedal force below 200÷250 N, using the power assistance system.

To exert control forces easily, it is assumed that the driver's foot is angled on the floor to reduce the torque on the heel.

This kind of operation is allowed for emergency braking only, while for ordinary braking, the pedal is depressed in the same way as the accelerator.

The clutch pedal can also be operated in two ways, according to design choices and driver's habits:

- with the heel on the floor;
- with the foot at a higher position for the first part of the pedal stroke, and resting on the floor at the end of the stroke (clutch fully disengaged).

The first mode is used for precision modulation, as for starting up on a grade. In this phase the pedal stroke is limited.

Because the force on the pedal should stay below 100 N, the foot position could be advanced without negative consequences on heel torque.

On the most common pedal boards, the hinge axis of the accelerator and brake pedal are different, while they are the same for clutch and brake pedals. To allow different strokes for the last two pedals the clutch pedal in rest position can be placed higher.

To avoid interference with other pedals when depressing a pedal quickly, the distance between pedal centers should be as high as the sole width, not less than 100 mm.

Steering wheel positioning is more complex and must take into account:

- a minimum relative distance from the pedal board to allow correct operation of the pedals; this implies a minimum distance of about 650 mm between the highest pedal, in rest position, and the lower surface of the steering wheel;
- a comfortable inclination for the steering wheel of about $30° \div 35°$;
- a rotation axis placed at least 300 mm from the middle of the vehicle, to avoid interference with the front passenger during steering;
- interference with the driver's leg while entering and exiting the car.

All decisions on controls position should be taken at the same time the body is outlined. Because of this, such decisions are rarely made by chassis designers.

A relevant indicator of steering wheel ergonomics is the force needed to turn the steering wheel at low speed.

This evaluation should be made by executing steering cycles, at low car speed (about $5 \div 7$ km/h), from stop to stop; steering wheel rotation speed should be between 100 and 150°/s.

The output of this test reveals the hysteresis cycle of the steering wheel, as explained in the first volume, in the section on power steering.

When electric by-wire transmissions have totally replaced mechanical controls, there will be much more freedom to position these controls than was possible earlier.

Major future developments include the possibilities of:

- using joy-sticks or other devices, instead of the traditional steering wheel;

- integrating other functions such as shift, brake and clutch control in the steering control;

- mounting the steering control on moving boards, to enhance vehicle accessibility and to allow driving from either side;

- personalizing controls depending on user needs, to allow disabled people, for example, to drive more easily.

Other information about controls is reported in the first volume.

18.3 SUBJECTIVE REQUIREMENTS

Vehicle testing by car manufacturers is not only the final verification of product competitiveness before the launch, but also a valuable instrument for establishing measurable system objectives.

Classic testing implies objective experiments that are defined by straightforward procedures that are not affected by the skill or the personality of the driver, and that lead to precise and repeatable results, allowing the immediate comparison of achieved with target values. This testing is by nature *objective*.

The limitation of this approach is that the correlation between these measurements and customer expectation is small.

Customer opinions are subjective, based upon an evaluation of the difference between what they actually obtain in a given car and what they think is a reasonable expectation; an acceptable result is conditioned by their experience with previous cars and what they learn from specialized magazines, discussions with others and advertisements.

Tests to evaluate these judgements are called *subjective* tests and do not require particular instruments or dedicated test facilities, because they simply reflect the customers' day by day experience.

Some function, to be interpreted, are simple such as dynamic performance; others, such as handling performance, are more complex.

The evaluation of dynamic performance consists of measuring variables (top speed, acceleration, pick-up, etc.), which, according to their type, satisfy the customer as their value is low or high. Nevertheless, it is very difficult to identify the correct value for each variable or to establish if a lower value in a particular variable (for instance, acceleration) can be tolerated, if it produces a better result in some other variable (for instance, fuel consumption).

The difficulty will be even greater if the optimum value for the understeering index of a new car has to be balanced against performance in the accelerator pedal release maneuver.

A simple way to overcome this difficulty is to perform *jury tests*, using potential costumers of the car under development; a jury test is a typically subjective test where subjective customer judgements on a homogenous cluster of cars are acquired and elaborated through the use of statistical methods. In this cluster of homogenous cars a prototype, representing the car under development, may also be included.

The proper execution of a jury test execution requires that cars to be evaluated are already built and have reached a satisfactory level of refinement. They would not be of use in the early stages of development as technical specifications are defined.

More often, jury tests and the analysis of their results are part of initiatives that are independent of the development of a specific product; they can be performed occasionally, to evaluate the development of competitors' products and consequent customer expectations. A test campaign like this can establish customer evaluation criteria and target values.

To develop technical specifications for a new car, a vehicle mathematical model will be applied that has been previously validated with experimental results.

Mathematical models will be used to assign to the components of the new vehicle technical specifications that match the results to be achieved in a virtual jury test, one that will be performed as soon as significant prototypes are available. Instead of potential customers, professional drivers from the company will be used, who will use the same evaluation methods as the customers in previous jury tests.

We will consider three examples, applied respectively to handling, to dynamic comfort and to fuel consumption; other requirements can be studied in a similar way.

18.3.1 Handling and active safety

In this section we will describe the approach that has been developed in many articles quoted in the references.

Manufacturers usually evaluate handling and active safety by using professional drivers, who are able to make comparisons, correct errors, and address chassis designers; the point is to correlate these judgements with subjective tests performed by potential costumers. These are eventually replicated with mathematical models to produce useful design tools.

In our references, dynamic behavior requirements are classified according to the scheme in Fig. 18.3.

The scheme suggests a classification that takes into account driving conditions involving lateral dynamics (driving in a curve), longitudinal dynamics (accelerating and braking) and the interaction between the two situations (braking and accelerating in a curve).

Driving conditions are classified as to driving ease or safety, as in emergency maneuvers; non professional drivers are able to evaluate maneuvers of the first kind, while only professional drivers are asked to judge the second kind.

		Driving easiness	Driving safety
Lateral Dynamics	Response	Steering activity Response speed Response progressiveness Roll Roll speed	Maximum lateral acceleration Stability Obstacle avoidance Roll-over
	Control	Selfalignment Center play Response graduality Reaction graduality	S. W. oscillation S. W. selfaligning speed
Longitudinal Dynamics	Response	Braking efficiency Response speed Traction Pitch Pitch speed	Maximum long. acceleration Stopping distance
	Control	Pedal graduality Force graduality Brake modulation	
Lat. / Long. Interaction	Response	Traction in curve	Braking in a curve Tip-in Tip-out

FIGURE 18.3. Fundamental requirements of longitudinal and lateral vehicle dynamics, which define handling and active safety.

For each driving condition it is important to be able to distinguish between vehicle response and control quality; for instance, power assistance is relevant to steering control quality, but not relevant for vehicle dynamic response.

In terms of lateral dynamics, steering activity is considered the quantity of work to be applied to this control (steering wheel) to obtain a certain result; response speed and response progressiveness[1] as proportional to the effects to the action on the command are also relevant. Roll angle and roll speed are also relevant for comfort and stability.

Viewing lateral dynamics in terms of control quality, again for lateral dynamics, self-alignement represents the ability of the vehicle to drive spontaneously on a straight line, while center play is relevant in evaluating the command insensitivity to small steering angles on a straight course.

Response and reaction graduality[2] are relevant to completing the judgement of steering wheel quality.

For the sake of brevity, we do not comment on requirements related to the interaction of longitudinal and lateral dynamics.

The sample of cars to be examined is finalized according to the result we want to obtain from this study; in the case we are summarizing, the sample is ample, in terms of car types (they were selected in different market segments), because this study is focused on the correlation between the subjective judgements of drivers and objective measures to be acquired during selected elementary standard maneuvers.

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[1]We can define progressiveness of a control the derivative of its output (i.e. braking force), with reference to its input (i.e. brake pedal force).

[2]We can define graduality of a control the derivative of the force or torque applied with reference to its stroke.

As the correlation is demonstrated, the sample can be limited to existing cars that are more similar to the new product under development.

The test jury must include professional and non-professional drivers, in order to evaluate both emergency and normal driving conditions and also to find out if there is any systematic bias between the two categories; the size of the sample (at least 20 people) must be chosen to allow a sufficient confidence level.

All cars are evaluated in free driving conditions, on a test track offering the necessary safety and a course suitable for highlighting all requirements under evaluation.

A questionnaire must be set up, to gather test results; its questions address the requirements under consideration and must include numeric scores; an overall verdict is also required.

All scores are subjected to statistical techniques to:

- eliminate scoring bias; many jurors use only a part of the scoring scale, assigning scores that deviate constantly from the average;
- eliminate those scores that are too removed from the average of the jury.

After this treatment, the correlation between single values and overall judgment is investigated, using a multiple regression analysis.

Figure 18.4 shows the result of this analysis; all scores are normalized on a decimal scale. Histogram f refers to the overall judgement.

The same cars were evaluated on open loop elementary maneuvers that were felt to be more finalized to the requirements under evaluation.

The following elementary maneuvers were applied.

- Steering pad, according to the ISO 4138 standard, on a curvature 40 m in radius, starting from a low speed up to the maximum safe speed.
- Lateral transient test, according to the ISO 7401 standard, followed by the steering wheel release maneuver (ISO 17288). Cars were driven at 100 km/h on a straight path and received a steering input to the desired value at steering angular speed of at least 200 $^\circ s^{-1}$; this value was maintained for 3 s and the steering wheel released for other 3 s. The accelerator pedal was kept in place during the maneuvers. The test was repeated for incremental steering wheel values, until a value was identified at which the vehicle does not stabilize.
- Overtaking test according to ISO 3888 standards, at 90 km/h; although this maneuver is a closed loop and was not created for objective evaluation, an objective measurement has been obtained by dividing the square average of vehicle lateral acceleration by the steering work. Delays between acceleration and steering wheel peaks have also been measured.

There is no direct correlation between a single subjective judgement and a single elementary objective maneuver; nevertheless, the multiple regression

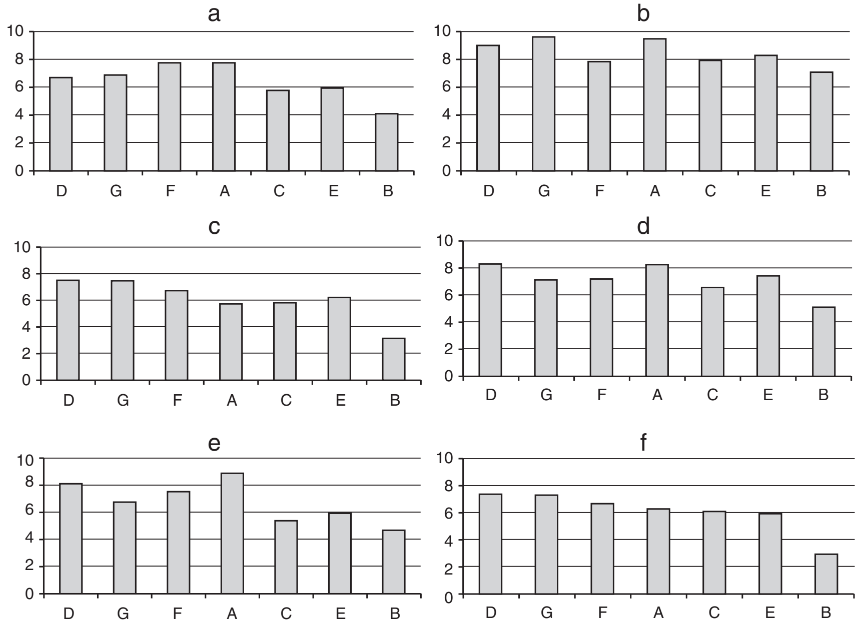

FIGURE 18.4. Average of subjective judgements on lateral dynamics of 7 cars; a: steering wheel activity; b: response speed; c: response progressiveness; d: roll speed; e: roll angle; f: overall judgement.

analysis relating each subjective judgement to all objective measurements under consideration returns an overall correlation factor of more than 0.85.

The correlation linear equations allow us to define partial *driving quality indices*, which correlate objective measurements, measured or calculated on elementary maneuvers, with subjective evaluations and, therefore, with customer satisfaction.

The *global driving quality index* in Fig. 18.4f is correlated to other indices with the same method and allows us to evaluate *a priori* the possible trade-off between these indices.

A similar process can be repeated for other groups of variables in Fig. 18.4, defining a global index that allows us to apply measurements to elementary maneuvers to forecast the customer's judgement on a car in terms of handling and active safety.

18.3.2 Dynamic comfort

This logical process has been also applied to the case of dynamic comfort, according to another article quoted in the references; although this work considers acoustic and vibration comfort as a whole, we will limit our analysis to vibrations only.

In this study drivers have driven their cars on open roads as they wish; the chosen road has been classified according to recorded acceleration on selected car positions.

The questionnaire was divided into three different parts.

The first one was addressed to vibrations perceived on different contact points with test cars:

- body floor;
- seat cushion;
- seat back rest;
- steering wheel.

The second part of this questionnaire solicited reactions to different perceived disturbances in the main movement of the vehicle; a follow-up variance analysis has suggested these results to not considered because of their excessive spread.

The third part was designed to gather an overall judgement; the scoring scale was again decimal, with scores of 10 assigned as the absolute optimum (no disturbances perceived).

Data on subjective measurements have not benefitted of standard elementary maneuvers, as in the case of handling; in their absence the following maneuvers have been used:

- random inputs on the motorway at 80, 100, 120, 140 km/h; on urban stone pavement, at 20, 40, 60 km/h; and on a low maintenance suburban road, at 20, 40, 60 km/h.
- shocks from a rectangular profile single obstacle across the road, at 30 and 50 km/h; on a rail level crossing at 20 and 40 km/h; and crossing a bump at 30 and 50 km/h; each obstacle has been reproduced on a track, by profiles elaborated statistically on open roads.

Acceleration measurements from random tests have been elaborated by calculating RMS in the domain of time and frequency. The same procedure has been applied to the shock test, including calculated magnitudes as, for instance, wasted energy, as well.

In this case, partial indices and a global index can be obtained that are well correlated to overall customer judgement and to the single measurements derived by elementary maneuvers.

18.3.3 Fuel consumption

Contrary to the previously described requirements, where customers have difficulty in formulating objective judgments about their satisfaction, fuel consumption is measured and recorded objectively by many customers. Even if this measurement is, sometimes, acquired without scientific methods, there is no doubt that these judgements about the car are more reliable than others.

The most difficult information to be obtained about fuel consumption is the effective driving conditions used by customers in evaluating it.

It is standard practice to include questions about fuel consumption on all questionnaires that car manufacturers send to their customer sample, to have feedback on their products after a short period of use.

According to a European Union law we will discuss in the next chapter, fuel consumption is measured on a roller bench on a simulated course reproducing urban, suburban and motorway traffic. Since this measure is the only allowed channel for customer information about fuel consumption, this procedure has been chosen instead of others to evaluate fuel consumption objectively.

This procedure is characteristically independent of vehicle performance and driving habits and imposes to all cars the same gear shifting speeds; if this first characteristic is justified by the high traffic density on our roads, the second and third have, as their justification, the need to make the test procedure objective and repeatable.

It is often the case that the results of this test, when compared with tests in actual traffic conditions, can suggest wrong judgements, when comparing different cars.

The interesting fact is that this result is not due to specific customer driving habits, but represents a phenomenon that can be detected with statistical procedures on a sample of homogeneous customers.

Similar criteria to those of previous examples have been applied to fuel consumption. We describe a recent research on medium size non-sporty cars.

Identifying potential customers is essential to defining the market for these cars. The customer's economic bracket influence the negative value assigned to high fuel consumption; relevant parameters may be car price (a high-income customer is less sensitive to fuel consumption than to comfort and consequent weight), yearly distance travelled and type of car. On a sporty car, for instance, driving habits are less mindful of consumption, while diesel cars are frequently driven by customers sensitive to this parameter.

This test campaign included 20 non-professional drivers using a homogeneous sample of recent cars. A driving mission was defined, including an urban, a suburban and a motorway section, representing real-world use of the car recorded over a significant period of time by each driver.

Departing from the standard driving cycle (correlation coefficient 0.77), a high correlation (correlation coefficient 0.97) was detected on this driving course with claimed fuel consumption, as previously determined by questionnaires yo potential costumers.

New driving schedules have been developed, to be performed on roller dynamometers, that are representative of each mission and driving habit.

The following approach has been adopted:

- for each car and driver, the statistical distributions of average speed, engine idling times, average positive and negative accelerations and average gear change speeds have been recorded and investigated;
- by comparing time histograms of the different gear speeds with car speed and acceleration, a map of gear shift speed has been obtained, as a function of longitudinal acceleration and speed;
- speed time histories on each mission have been analyzed from start to stop, identifying any cluster where similar sequences have been grouped.

A new urban and suburban cycle has been identified; the important characteristic of these new cycles is not relevant to car speeds which are slightly higher than standard speeds, but is remarkable that the speed shift criterion depends upon car pick-up time; the higher the available torque exceeding driving resistance, the lower the vehicle speed where the gear is upshifted.

It should be remembered that this first conclusion is not applicable to all cars, but is limited to the kind of car, customers and driving environment to be considered.

Figure 18.5 demonstrates our conclusion. On the two diagrams on the right, showing the upshift speeds, measured in [km/h], as a function of the longitudinal requested acceleration, measured in [g] a car with a peak torque at high engine speed is shown; on the left diagrams the same car with peak torque at lower

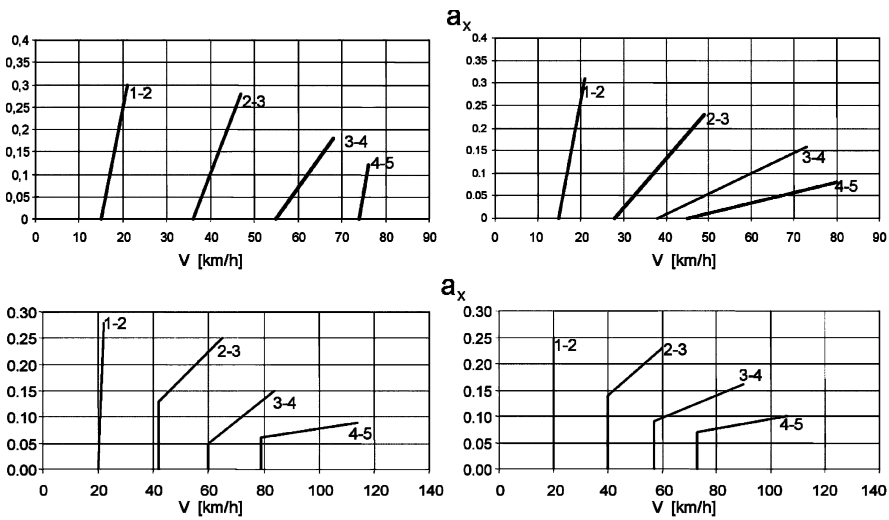

FIGURE 18.5. Comparison between upshift speeds for two cars of almost equal mass and displacement in urban traffic (above) and suburban traffic (below), as a function of the requested longitudinal acceleration a_x, measured in [g]. The engine of the car shown in the diagram on the right is designed to have its peak torque at higher engine revolutions.

engine speed is shown. The upper diagrams refer to urban driving, the lower to suburban driving.

The engine with higher elasticity induces drivers to lower upshift speeds for low accelerations; since accelerations between 0.12÷0.20 g are frequent in urban traffic and between 0.02÷0.07 g are frequent in suburban traffic, the more elastic engine is used, in the average, at lower rotational speeds, with higher gears.

Vehicle fuel consumption is strongly influenced by gear ratios; in general, we may say that in the prevalent conditions of use, fuel consumption is almost proportional to engine speed.

If in theory the availability of higher transmission ratios favours reduced fuel consumption in standard cycle, the conclusion of this work suggests that these reductions will not be achieved if the reduced pick-up capacity of the car stimulates drivers to use lower ratios more frequently.

Motorway consumption in this test campaign was sufficiently correlated with the traditional test procedure; under these conditions, the highest ratios were used.

Measured driving distances were equally divided over the three driving environments.

18.4 AGING RESISTANCE

A car's endurance, or resistance to age, is a function that can be evaluated objectively by driving it for a specified distance without damage.

We must clarify what we mean by damage; during the life of a car, customers ask not only for few failures, but little deterioration of those parameters found in a new car.

In the case of the automotive chassis, we mean also that requirements about:

- dynamic performance,
- handling and active safety,
- dynamic comfort,
- ergonomics,

can deteriorate only within an acceptable range of tolerance; in addition, nothing that can affect vehicle availability (to perform its function), can occur except through the fulfillment of scheduled maintenance.

Failure include, therefore, not only breakdowns of mechanical or electric parts, but also noise not detectable on a new vehicle, lubricant leakages, aesthetic corrosion, changes in dynamic behavior, fuel consumption, freedom of movement on controls, etc.

It is hard to forecast how the vehicle will be used, because use is conditioned by the life and driving style of the customer; in addition, applied loads can be determined by unforeseeable events.

Therefore, endurance specifications are assigned statistically often using the parameter B_{10}, which defines the endurance achieved without any failure by 10% of the population of vehicles produced.

As a reference for the value of this parameter, we can assume as adequate for today production, about:

- $B_{10} \geqslant 200{,}000$ km, for cars and commercial vehicles;
- $B_{10} \geqslant 400{,}000$ km, for buses;
- $B_{10} \geqslant 800{,}000$ km, for heavy duty trucks.

As technology and the market are evolving continuously, it is possible that these values will increase in the future.

These travelling distances make it almost impossible to perform, in the standard delay time of 3÷4 years on the average devoted to a new vehicle development, the tests needed to assess endurance experimentally, after design and prototype manufacturing, with a sufficient confidence level; nor can this job be reasonably assigned to mathematical models.

In the case of cars, a life of about 200,000 km implies, on average, 4,000 h of driving time, assuming standard driving tasks; if we allocate six months for this task, as usually occurs, then to perform two complete sets of tests on two different prototypes generations (where the second carries corrections for the first), the test time must be shortened by at least 3÷4 times.

Phenomena that can influence the endurance of a vehicle can be classified according to the following categories:

- fatigue;
- wear;
- corrosion;
- shocks and collisions.

External fatigue loads that can stress chassis components arise from two different sources: tires and engine.

Tires apply to the chassis longitudinal, lateral and vertical forces, changing over time; the first and second act with the frequency (on average low) of acceleration, braking and cornering events along the path of the vehicle; the last act with the higher frequencies given by the shape and spatial density of obstacles overcome.

The engine stresses the chassis at usually low frequencies, determined by the schedule of maneuvers (acceleration, releases, shifts) and at higher frequencies determined by its reciprocating parts.

Other periodic forces may be added when some of the above is working near the natural frequencies of the structures it is applied; this is particularly relevant for chassis structures and transmission.

Subject to fatigue are suspension and steering arms, wheels, bearings, springs, some braking parts (calipers, controls), transmission shafts, gears and chassis structures.

Most of these parts are made out of metals whose resistance can be described according to Wöhler's model; there is a threshold of load amplitude (fatigue limit) for these materials which can be applied indefinitely without any damage.

For this category of parts, test times can be reduced by applying techniques that remove the periods of load history below the fatigue limit. This can be done precisely by analyzing load time histories that will be applied to bench tests or by driving cars in more strenuous tests that apply loads that damage structures more severely.

Using this last approach the driving distance of a car's life can be condensed into about 50,000 km of heavy use.

Wear is determined by the friction of parts in relative motion; on the chassis, wear applies mainly to transmissions (bushings, rotary and sliding seals, synchro mesh and gears) and partly to suspensions.

Wear, the removal of material on sliding parts, depends on wasted friction, according to the hypothesis proposed by Theodor Reye about 140 year ago. Wear can therefore be accelerated by increasing loads, with attention to temperatures, that can affect the mechanical properties of materials.

A wear test for components can be reliably performed on test benches, where contact conditions are made more severe according to empirical procedures.

Corrosion is caused by the chemical action of many agents (humidity, salts, other chemical compounds and aerosols) on parts exposed to the atmosphere or splashed by the wheels; since this action is not constant throughout the life of the car, the test can be accelerated by exposing entire cars or components to corrosive humidostatic rooms for a certain period.

Another method, as effective as the first, is to drive through acid water pools during a certain portion of the fatigue course.

As we have seen, wear and corrosion test acceleration is totally empirical and is defined according to the manufacturer's experience.

Vehicle resistance to shocks and collisions must be examined through artificially reproduced events.

This applies to crash tests against barriers, requested by regulations, where chassis components must not interfere with occupants as a consequence of the collision.

There are also non-regulated shocks, where it is good practice to verify that there are no critical situations for occupants; one example of this category is the accidental collision of wheel against sidewalk, as a consequence of a mistaken maneuver; it is obvious that in these cases chassis structural integrity is not requested.

The designer must guarantee that there are no partial or hidden ruptures undetectable by the driver. Linkages and suspension arms must feature a rupture load at least 50% higher than the collapse load, where deformations become permanent; deformations, prior to rupture, must alter suspension geometry in such a way as to be easily noticeable by drivers, in order to suggest trip interruption.

Vehicle life is simulated by separate tests reproducing specific situations; fatigue tests are more difficult because they are determined not only by their duration but also by conditions of vehicle use.

Each manufacturer has decided to design vehicles for the most demanding conditions, accepting high safety margins for ordinary use; loop courses have been developed that are characterized by many bends, bumpy and uneven stretches (artificially damaged tarmac, stone pavement, dirty road, etc.) and rail crossings; a part of these courses is dedicated to water-crossing.

Such loops, if driven at high speed, can concentrate 200,000 km of real life into about 50,000 km, driven in about 1,000 h; this time corresponds to about two months, assuming three driving shifts on the same car, and including test interruptions to maintain and inspect the test prototype.

Load conditions to be considered in mathematical models or applied to test benches are also derived from this kind of loop.

A common test loop includes straight stretches long enough to allow the car to reach the highest acceleration and deceleration conditions; curves are driven at the slip limit.

Loop length is not relevant, because it will be repeated in both driving directions so as not to stress the vehicle in a selective way, until the total driving distance is reached; loop length is conditioned by the need to apply all tests suitable for simulating the most demanding driving situations. Usually these loops are between 20 and 30 km in length.

Pavement must offer a high friction coefficient to stress suspensions and chassis as much as possible. Sometimes, on long straight stretches, signals can be used to request additional maneuvers (decelerations, accelerations, slaloms).

Figure 18.6 shows a record of the main force components acting on a medium size car on a loop of this kind.

Instead of vertical forces suspension strokes have been measured; vertical forces may be calculated from suspension characteristics. Brake torque has also been added to separate transmission effects from those of the brakes in longitudinal forces.

These records originate from test bench load conditions, after mathematical elaboration; the same conditions can be applied to finite elements analyses, which are usually integrated into multibody models to simulate the entire vehicle.

Reorganization of the test cycles can be performed according to the rain flow method; the result is a set of load histograms, shown in Figs. 18.7, 18.8, 18.9, representing suspension stroke as well as longitudinal and lateral accelerations. Accelerations are derived by forces with reference to the sprung mass and can be applied to different cars as well, as a first approximation.

These histograms define the so called *load blocks* which correspond to driving the entire loop, about 30 km long, once clockwise and once counterclockwise; the load block is applied about 2,000 times to simulate the entire vehicle life.

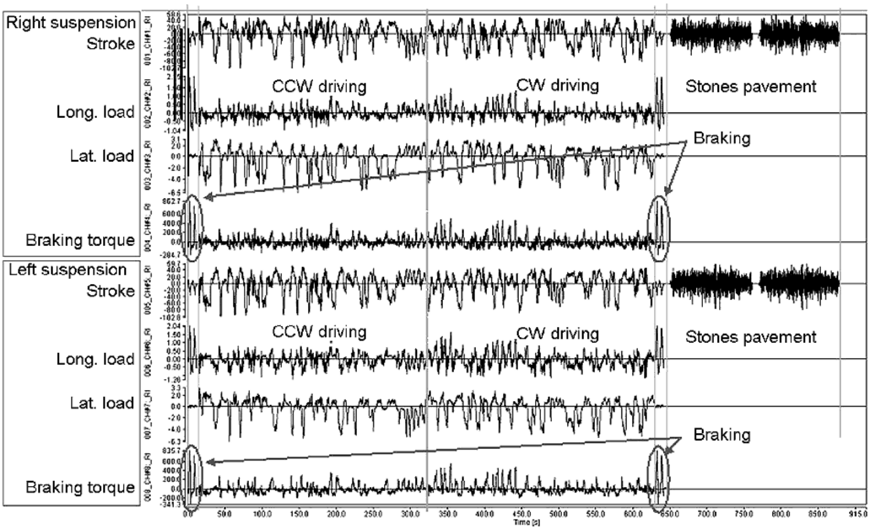

FIGURE 18.6. Records of suspension strokes, showing longitudinal and lateral loads on rear suspensions of a medium size car, driven on a fatigue loop clockwise (CW) and counterclockwise (CCW).

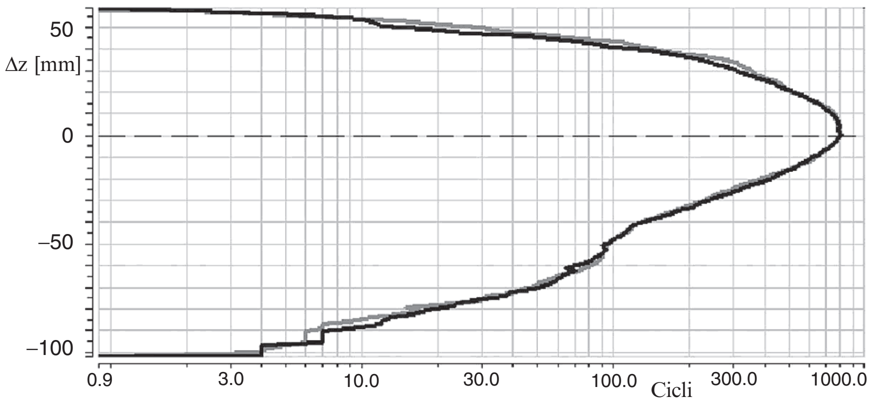

FIGURE 18.7. Histogram showing the cycle count of different suspension stroke classes Δz of right and left rear suspensions, on a fatigue loop.

It should be noted that accelerations refer to sprung mass; acceleration values apparently inconsistent with practical friction coefficients are not surprising, because vertical loads are increased by transfers due to lateral accelerations.

Figure 18.10 shows a bench for fatigue tests of a car body, complete in its main chassis components; actuators for applying loads and torques are also shown. The front wheel can be stressed similarly.

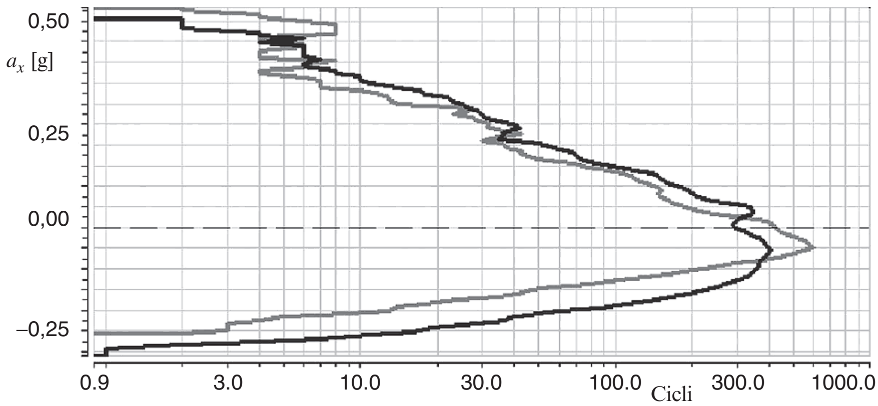

FIGURE 18.8. Histogram showing the cycle count of different longitudinal acceleration classes a_x of right and left rear suspensions, on a fatigue loop.

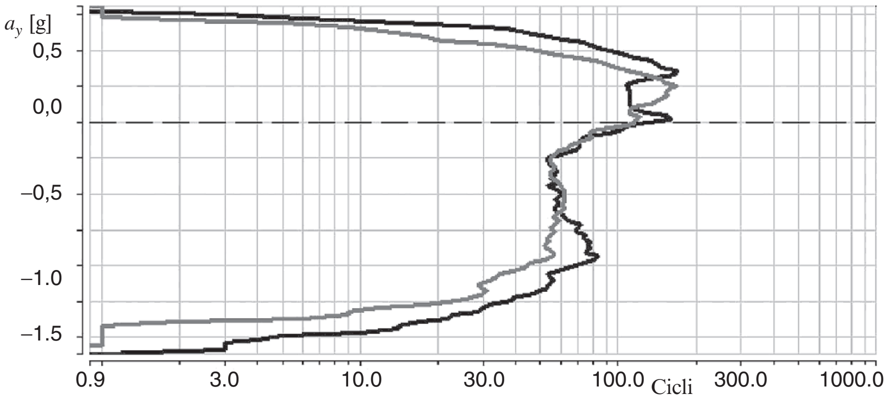

FIGURE 18.9. Histogram showing the cycle count of different suspension longitudinal acceleration a_y of right and left rear suspensions, on a fatigue loop.

Dynamic analysis of these forces assumes a particular importance if we want to determine fatigue load for particular components under specified driving conditions.

Usually the entire vehicle simulation applies multibody modeling techniques that are useful when displacement is relevant; these models allow not only displacement but also forces exchanged in any part of the system to be calculated.

In multibody modeling, system elements are considered as rigid bodies connected by elastic or viscoelastic couplings. In some cases, it is necessary, for a more precise determination of acting loads, to also take into account the flexibility of some part, such as the car body or the twist beam of a rear suspension.

Craig-Bampton's theory allows the flexibility of specific vehicle structures by their modal synthesis to be taken into account; this can be obtained by a finite element calculation of the modal deformations.

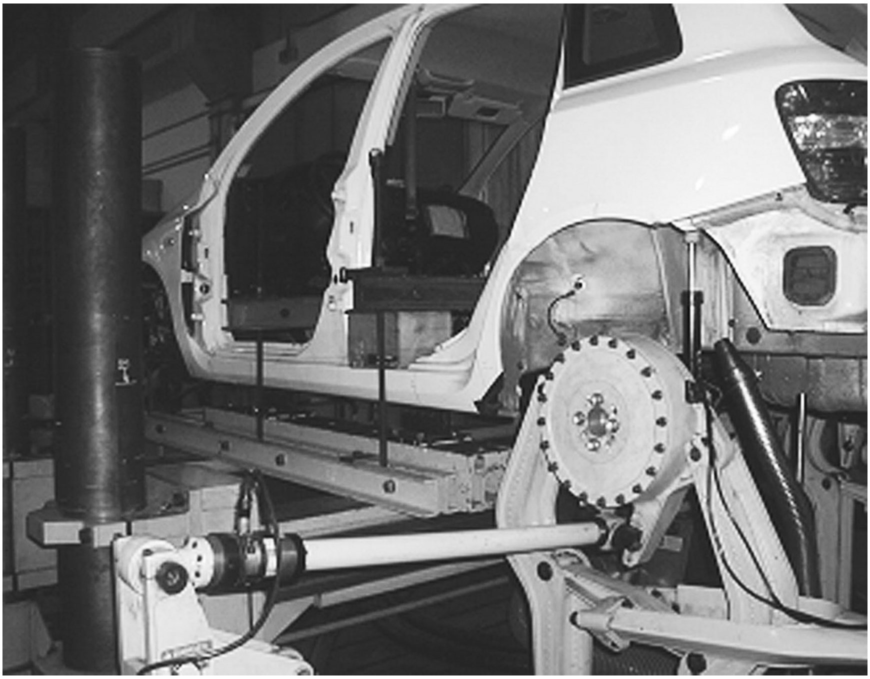

FIGURE 18.10. Fatigue test bench for a car body, complete with the most important chassis components; actuators supply rear suspension forces and torques.

In practice, for a specific structure:

- the displacements of the structure, compatible with its degrees of freedom, are evaluated as the result of a unitary force applied;
- the vibration modes are calculated, in a range up to about 100 Hz.

These data are applied to the multibody model, to determine the internal forces exchanged between the different components.

A multibody model of the vehicle system should include at least:

- the car body, as rigid body or as flexible body, according to the scenario under study;
- the powertrain mass and its suspension;
- the complete front and rear suspensions;
- tires, when loads are calculated from an open loop maneuver of interest.

The different parts are connected by joints, showing a suitable elastic and viscoelastic characteristic; mass and inertia properties are calculated for each of them.

If we refer to the previously described scenario, the same input for the test bench of Fig. 18.10 can be adopted as input of the multibody model.

The output of this analysis should be the forces that are exchanged at the articulation point of the suspension to the car body.

These forces may be applied to finite element models addressed to calculate the stress histories of the component under study, to determine the fatigue life of this element.

This calculation can be performed in two different ways, due to the fact that there is some overlap between force frequencies and natural frequencies of the component under investigation.

If there is no overlap, forces can be applied quasi-statically. A stress time history can be easily obtained by linear combination of the different effects.

If there is some overlap, dynamic modal techniques must be applied.