Chapter 1

The Automobile Body

The automobile body, Figure 1.1, is an important vehicle subsystem that performs many functions [1]. These range from the very basic function of being the armature holding the parts of the vehicle together, to the function of noise and vibration refinement which differentiates a luxury vehicle from an economy vehicle. In this chapter, we briefly describe the contemporary body structure and terminology.

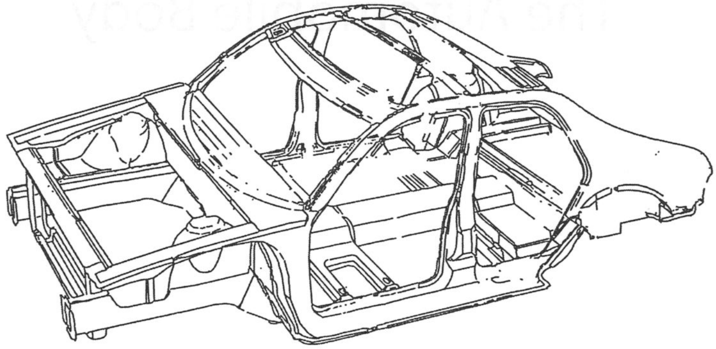

Figure 1.1 Typical body-in-white. (Courtesy of General Motors Corporation)

A typical body is an assembly of metal stampings, Figure 1.2, usually of steel but also of aluminum. Several material grades or alloys are used to meet the structural requirements at the formability needed to achieve the part shape, Figure 1.3 [2]. The stampings are assembled to form thin-walled structural elements, Figure 1.4. The general arrangement of these structural elements leads to several different body types.

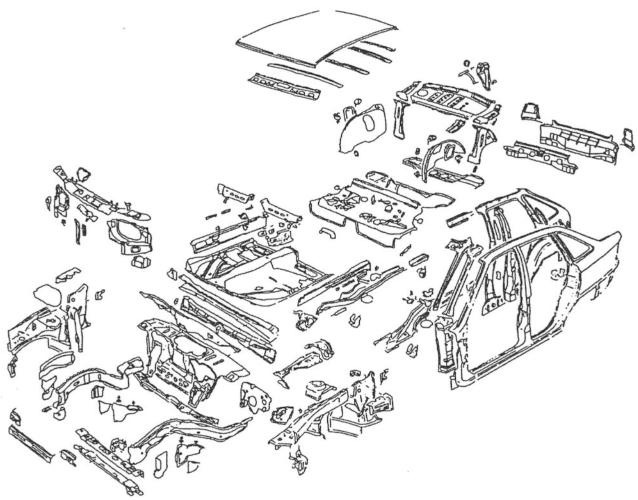

Figure 1.2 Body stampings. (Courtesy of General Motors Corporation)

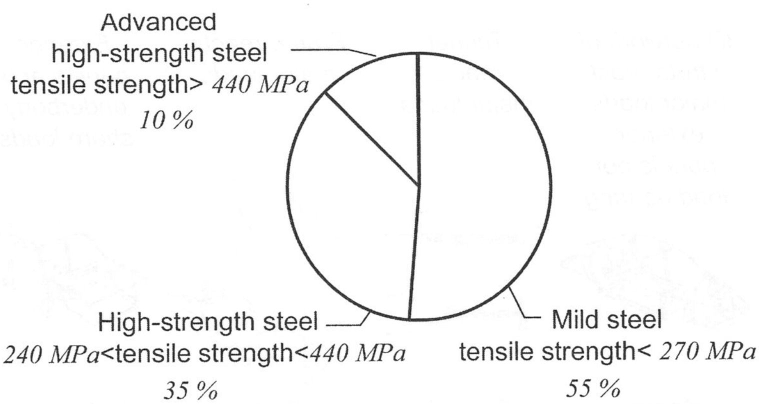

Figure 1.3 Range of steel grades in typical car.

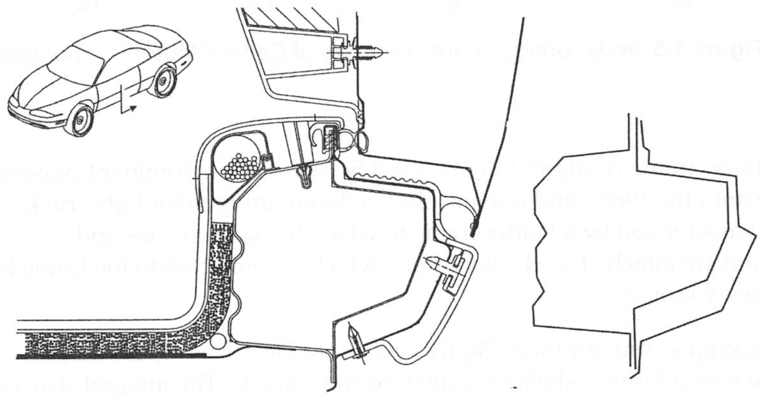

Figure 1.4 Typical section at rocker. (Courtesy of General Motors Corporation)

1.1 Description of the Automobile Body Types

There are several types of body structure configurations today. The predominant types are space frame, central frame, body-on-frame, and monocoque (integral body-frame), Figure 1.5.

The space frame configuration, Figure 1.5a, is characterized by a three-dimensional framework of beams connected at nodes. The framework provides the structural integrity with the exterior panels being unstressed. The space frame type can be fabricated using lower-cost tooling such as roll forming or hydroforming, and is usually targeted for lower-volume vehicles.

The central frame configuration, Figure 1.5b, is characterized by a large, closed structural member down the center of the vehicle. This member provides the structural integrity for this type. Because of the intrusion into the cabin, this arrangement is limited to two- or four-seat interior configurations.

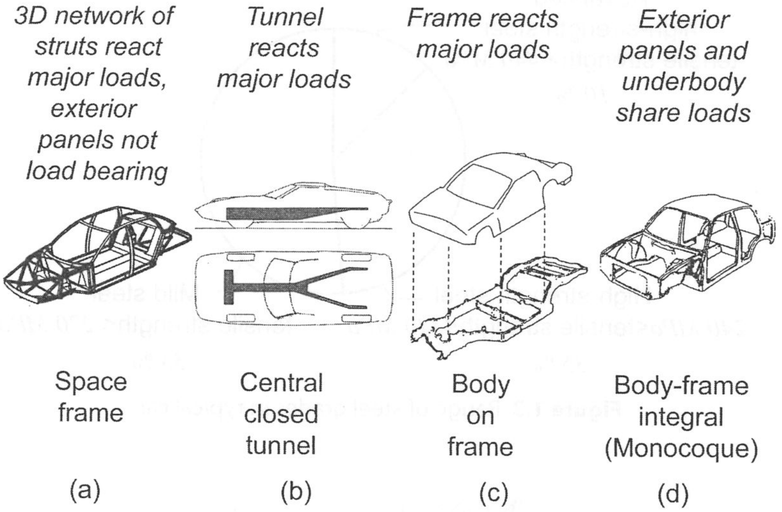

Figure 1.5 Body configurations. (Courtesy of General Motors Corporation)

The body-on-frame configuration, Figure 1.5c, was the predominant passenger car type until the 1980s, and remains the predominant type for light trucks. This type is characterized by a ladder frame to which the suspensions and powertrain are attached, and a body shell which is connected to the frame by flexible body mounts.

The monocoque configuration, Figure 1.5d, is characterized by an integral structure which forms a shell, including exterior panels. The integral structure reacts to all major loads. This is currently the predominant type for passenger cars, and is considered the most mass-efficient configuration. Because of its predominance, this book will focus on the monocoque configuration; however, the principles we will develop are also applicable to the other configurations as well.

Within the monocoque configuration, there are topology variants. *Topology* is the arrangement of structural elements—beams and panels—to meet requirements in the most efficient manner. Besides structural concerns, an effective body topology also satisfies the additional constraints which the package, styling, and manufacturing place on the positioning and size of structural elements. Figure 1.6 shows three of the most common monocoque topologies in use today [3]. In later chapters, we will discuss the fundamentals of determining a body topology.

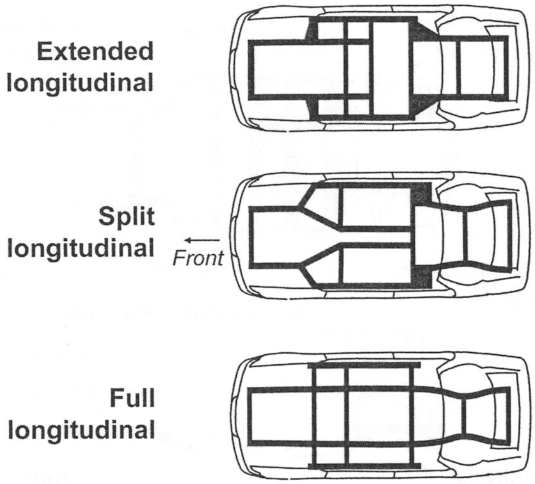

Figure 1.6 Body-frame integral typical topologies.

1.2 Body Nomenclature

While a uniform naming convention for body structure elements does not exist, there are some more common terms in use. Figures 1.7 through 1.10 show common names for the major structural elements with respect to the overall body. In Figures 1.11 through 1.16, part names are shown in a useful hierarchical format. This hierarchy follows a typical manufacturing partition of the body structure.

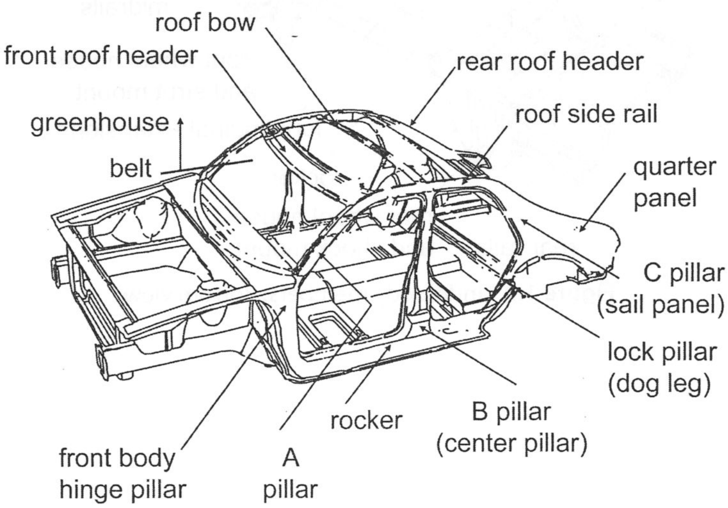

Figure 1.7 Side and greenhouse members.

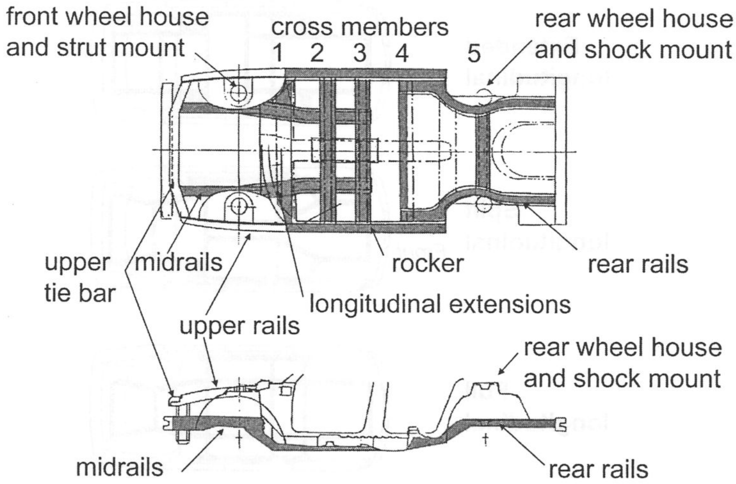

Figure 1.8 Underbody members.

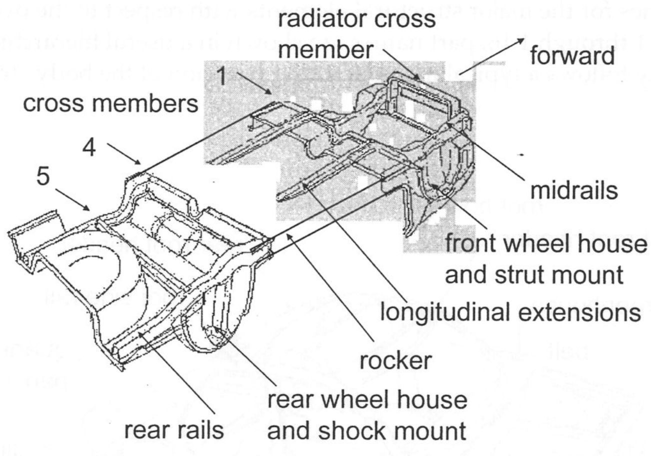

Figure 1.9 Underbody members: Bottom view.

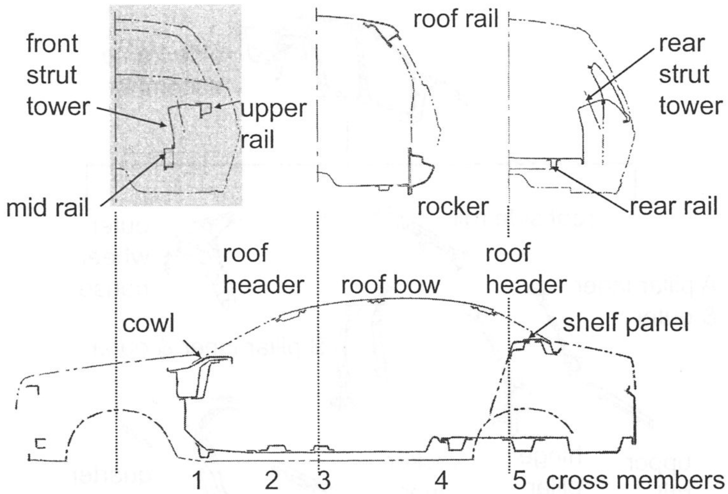

Figure 1.10 Body cross sections.

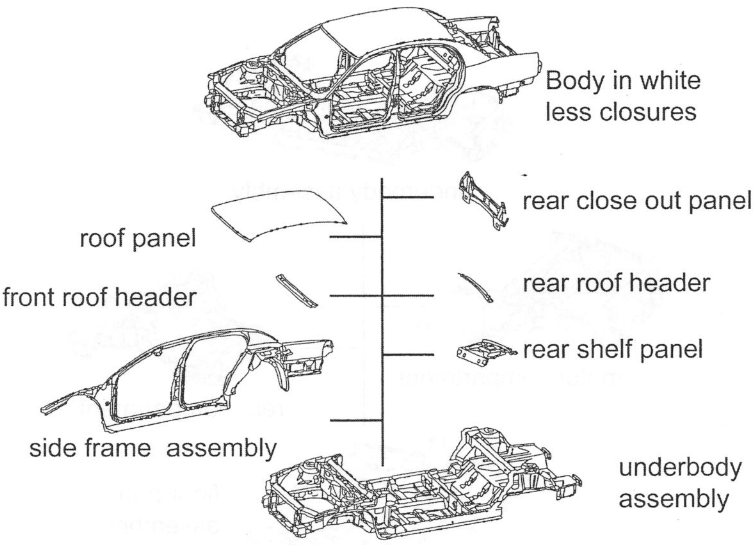

Figure 1.11 Body in white. (Courtesy of General Motors Corporation)

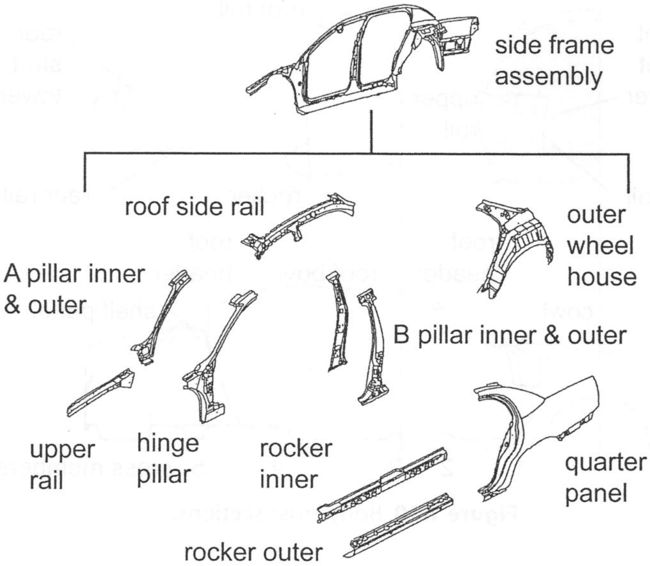

Figure 1.12 Side frame. (Courtesy of General Motors Corporation)

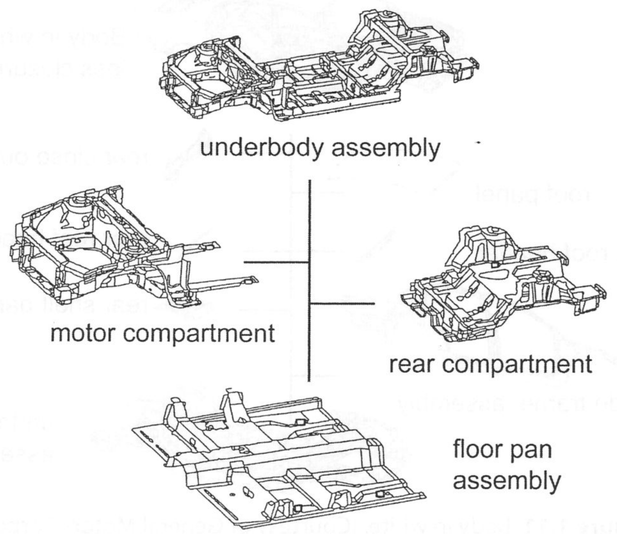

Figure 1.13 Underbody. (Courtesy of General Motors Corporation)

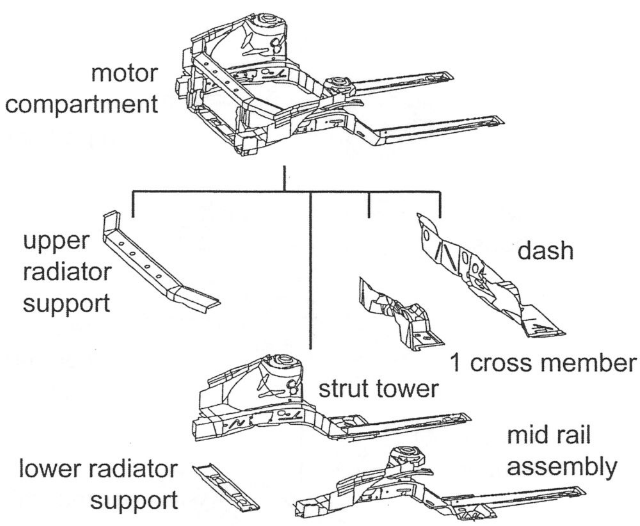

Figure 1.14 Motor compartment. (Courtesy of General Motors Corporation)

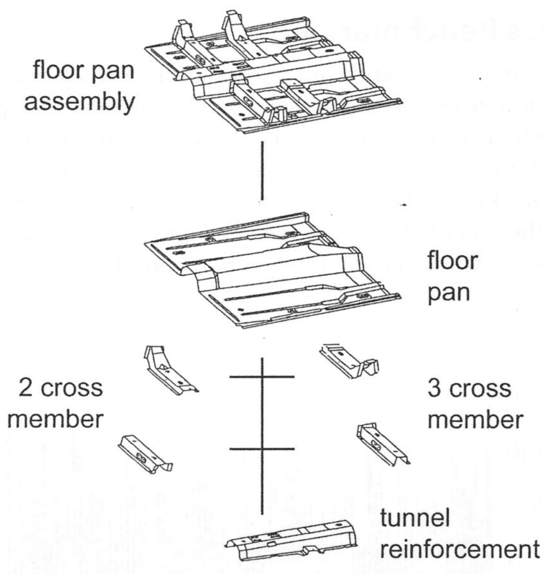

Figure 1.15 Floor pan assembly. (Courtesy of General Motors Corporation)

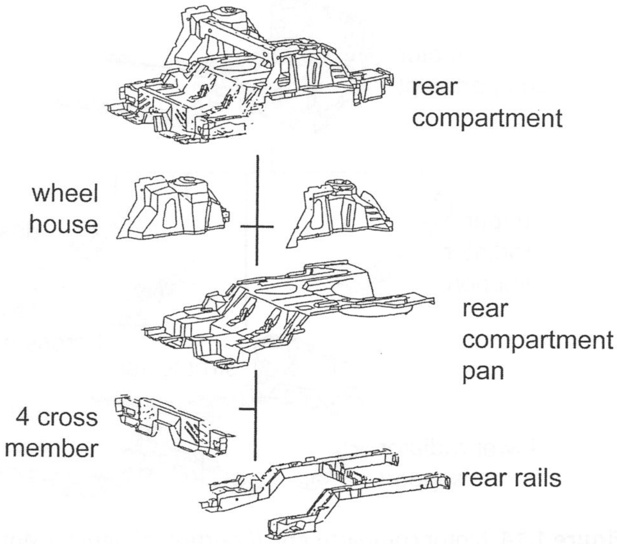

Figure 1.16 Rear compartment. (Courtesy of General Motors Corporation)

1.3 Body Mass Benchmarking

The body structure mass is a significant portion of the vehicle mass, and because of this, the body influences mass-sensitive vehicle functions such as fuel economy, acceleration performance, and handling. Looking at the body shell mass (no trim, glass, closures, or bolt-on panels) for several sedans, Figure 1.17, the average mass is approximately 325 kg (715 lb) [4]. A more useful way to look at body mass is in comparison with the other vehicle subsystems. Figure 1.18 shows this breakdown for a typical mid-size vehicle having integral body and front wheel drive.

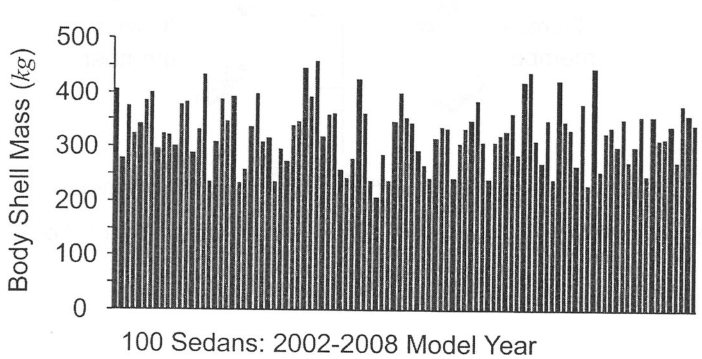

Figure 1.17 Body shell mass.

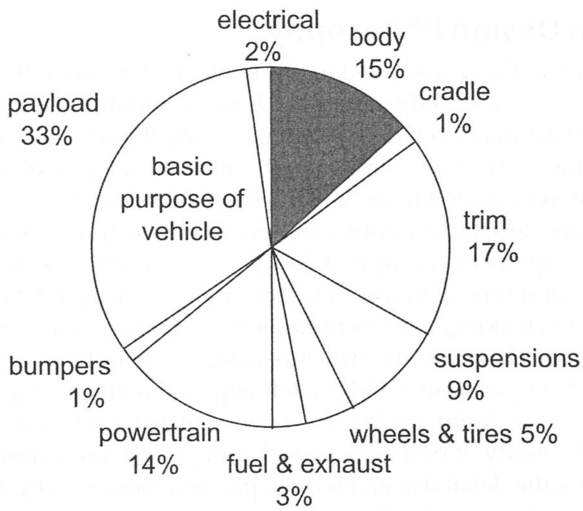

Figure 1.18 Vehicle mass breakdown.

As we are often interested in structural efficiency, it is useful to look at the body structure mass normalized by the gross vehicle mass [5]. This tells us how much structure mass is required to provide support for a unit mass of the vehicle. Figure 1.19 shows this useful ratio for several vehicles as well as other man-made and natural systems.

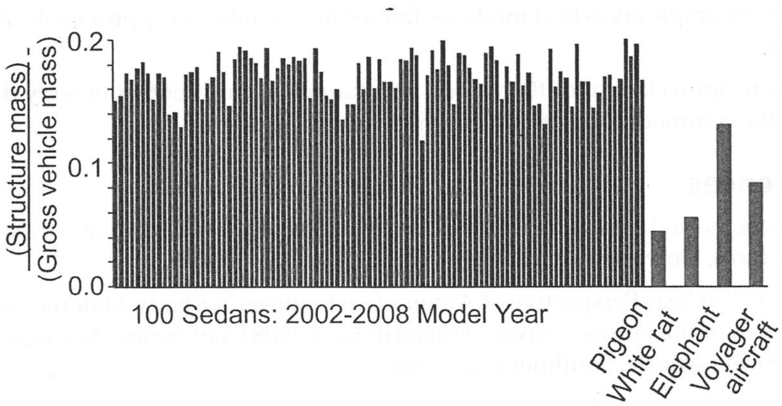

Figure 1.19 Normalized body structure mass.

1.4 The Body Structure as a System

Throughout this book, we will use the systems engineering approach to treat automobile body design. A system may be described in two ways: The first is by a breakdown of its physical parts or subsystems. The second is by examining the functions the system must provide. For example, in Section 1.2, we described the body using a breakdown by parts. In the next chapter on requirements, we will describe the body system by looking at the functions it must perform within the larger vehicle system (the systems engineering approach).

1.5 Note on Design Philosophy

The concepts and methods discussed in this book are directed at the *preliminary design stage* for automobile body structure. During preliminary design, the vehicle mission is translated into a vehicle concept including the selection of subsystems, layout, and styling to meet the mission. In the absence of a preexisting design, the body structure is synthesized from "a blank sheet of paper" during preliminary design. Frequently, design data during this phase are fuzzy and changing. Also, the vehicle design is rapidly evolving, and design decisions must be made rapidly, often within a turn-around time of hours. This lack of precise design data, and need for very rapid decision making, renders finite element analysis difficult to apply during preliminary design. Therefore, the structure designer relies heavily on *physical intuition* and *first-order analysis models* in defining load paths, sizing structural elements, and making design trade-offs. Having created a solid preliminary design, the number and severity of problems passed along to the detail design phase is reduced, allowing the detail design phase to proceed more rapidly. During the later detail design phase, application of physical intuition is again valuable in interpreting and sense-checking finite element analysis and test results.

The goal of this book is to help the reader develop this physical intuition for body structure layout, particularly developing the abilities to:

- Identify the small set of topology-defining structural requirements
- Gain an intuitive feel for thin-walled structure behavior
- Develop simple analytical models—first-order models—to approximate structure sizing
- Gain an appreciation for the vehicle and manufacturing context of body design and the common trade-off issues which must be balanced

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2. Hall, J., "50 Year Perspective of Automotive Engineering Body Materials and an Analysis of the Future," Great Designs in Steel 2008 Conference, American Iron and Steel Institute, Southfield, MI, 2008.
3. Fenton, J., *Vehicle Body Layout and Analysis*, Mechanical Engineering Publications, Ltd, London, 1980, p. 12.
4. A2Mac1.com Automotive Benchmarking, Auto Reverse Database, www.a2mac1.com, Ypsilanti, MI, 2009.
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Chapter 2

Body Structural Requirements

Throughout this book we will use a systems engineering approach, Figure 2.1, to design body structure [1, 2, 3]. That is, we will first consider the function of a particular structure element. From the function we will identify structural requirements which the structure element must meet to fulfill its purpose. Then, based on the requirements, a specific structure concept will be synthesized. It is the intent that the analyses and examples provided in this book will give the reader considerable physical insight in efficiently synthesizing these preliminary design concepts. Finally, because our insight is not complete, we must evaluate the performance of our design concepts by test or by analysis, and compare the performance to the original requirement. Often, a gap between performance and requirement will be the case. When this occurs, corrections and refinements to the design concept are needed, and the process becomes iterative.

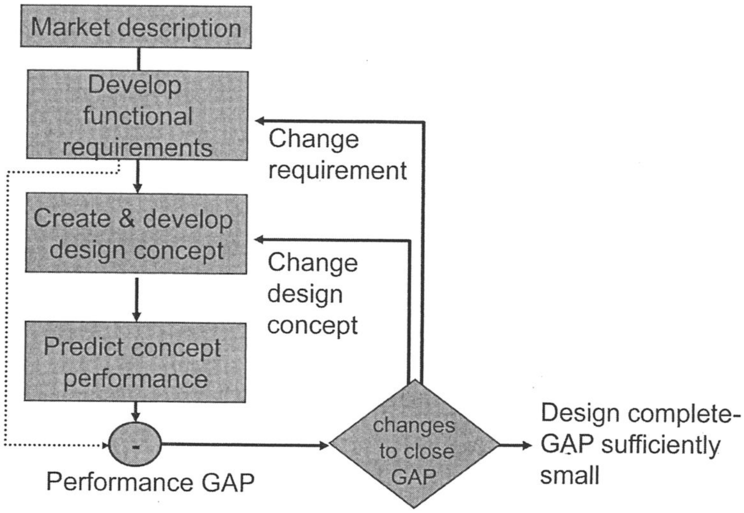

Figure 2.1 Systems engineering approach.

Requirements are then important as they are used to form the initial design concept, and then are used to guide the development and refinement of the concept. In this chapter we will consider a general approach to develop automotive body structural requirements.

2.1 Categories of Structural Requirements

Before looking at the specific case of automotive body structure, we will first consider the function of any general structure. At a basic level, the purpose of any structure is to:

1. React *loads* applied to it during use
2. React those loads with an amount of *deformation* which enhances (or does not restrict) the function of the system which the structure is part of.

Therefore, in considering structural requirements, we are dealing with *loads* and *deformations*. A helpful way to look at the reaction of a structure to loading and the resulting deformation is with the tensile test, Figure 2.2. In a typical test, the structure rests on the stationary bed and is loaded by a moving platen. As the platen imposes a displacement on the structure, the resulting reaction load is measured at the bed. Moving the platen through a displacement range and measuring the load reaction results in a load/deflection curve for the structure.

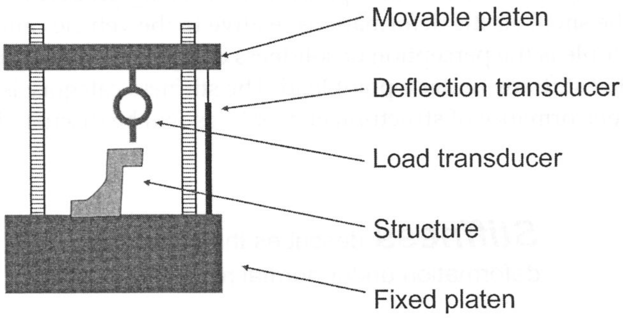

Figure 2.2 Tensile test machine.

A typical load-deflection curve, Figure 2.3, shows several regions; initially there is a linear region which is elastic—when the load is removed the deformation returns to zero. With increased load, some structures exhibit a nonlinear but elastic region. At some load, the structure will become inelastic; that is, when the load is removed there will remain some small permanent deformation. Continuing to increase deflection, the load will reach a maximum or ultimate load. Finally, at some maximum deformation, the structure will experience a catastrophic failure which can include a fracture (load goes to zero) or a bottoming out (load becomes very large).

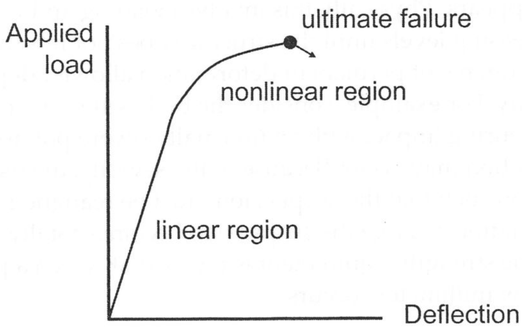

Figure 2.3 Typical load-deflection curve.

Earlier we said the purpose of a structure is to react to loads with an allowable deformation. It is useful to categorize structural requirements based on allowable deformation. What constitutes the particular allowable deformation depends on the function being satisfied by the structural element; the element's load-deflection curve helps categorization [4].

In the *stiffness category*, the deformations are small and elastic, and are characterized by stiffness—the ratio of applied load per unit of deformation, Figure 2.4. An example of an automotive structural requirement in the stiffness category is body stiffness at a suspension attachment point. The handling properties of the vehicle depend on the small elastic deformations relative to the vehicle center of mass. Another example is the perception of solidness of a panel, which is related to the panel's normal stiffness under a point load. The stiffness category is closely related to vibration performance of structural elements, as will be discussed in the chapter on vibration.

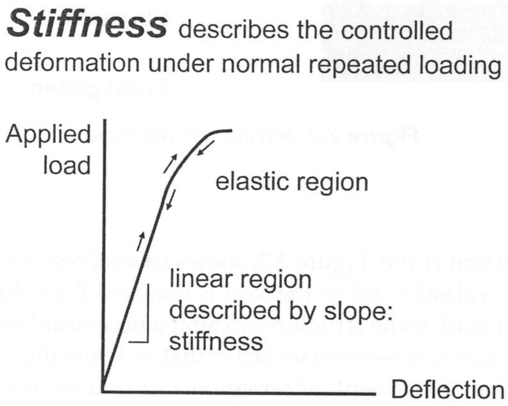

Figure 2.4 Stiffness behavior.

The *strength category* is characterized by the onset of a small permanent deformation, Figure 2.5. Here the requirement is stated as the lowest load at which a permanent deformation first appears. Physically this involves loading and unloading the structure with increasing levels until the structure does not return to its original shape. The specific degree of permanent deformation allowed depends on the loss of some functionality. For example, consider the body strength at a suspension attachment point. During impact with an unusually severe pot hole, a small permanent deformation may occur. Because of the severity, the user may expect a loss of some function such that the suspension must be realigned. The user would not expect a deformation so large the suspension becomes totally nonfunctional. Thus in this case, the strength requirement is the load at which a permanent deformation of a few millimeters occurs.

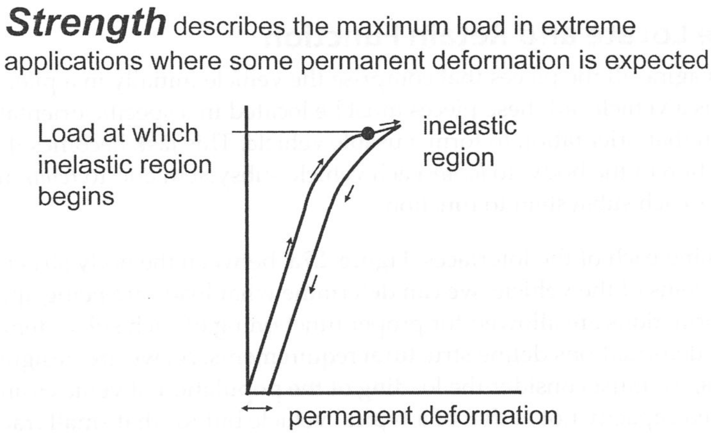

Figure 2.5 Strength behavior.

The *energy absorption category* is characterized by very large permanent deformations where the amount of energy absorbed by the structure during deformation is of interest, Figure 2.6. The requirements in this category can be stated in terms of the area under the load-deformation curve, or as an equivalent square wave load having the same contained area. An example of an energy absorption requirement is the average crush force generated by the motor compartment midrail during a front collision. While all structural elements will have stiffness and strength requirements, only a subset will have energy absorption requirements.

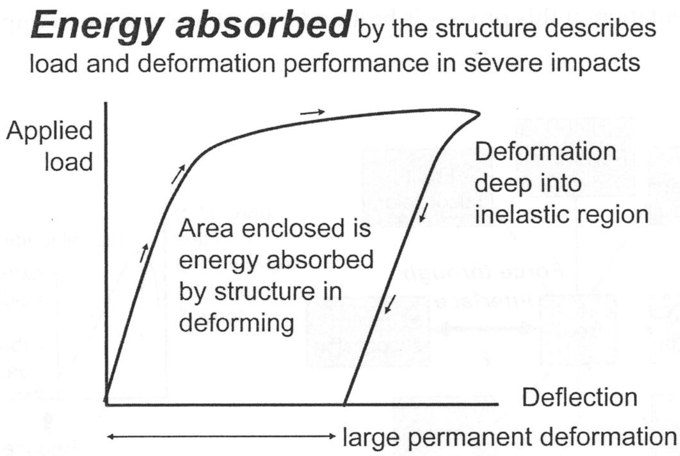

Figure 2.6 Energy absorption behavior.

The task of the automobile body designer is to create a structure with these three qualities of strength, stiffness, and energy absorption at the required levels. In the sections following, we begin to look at the sources of those structural requirements.

2.2 The Locate and Retain Function

We can imagine all the pieces that comprise the vehicle initially in a pile. In order to function as a vehicle, all these pieces must be located in a specific orientation and retained in that orientation to form a usable vehicle. This task becomes the most basic function of the body: to *locate* each vehicle subsystem and to *retain* it in a way that allows each subsystem to function.

By examining each of the interfaces, Figure 2.7a, between the body structure and the subsystems of the vehicle, we can determine what loads are being applied and what deformations are allowed for proper functioning of each subsystem. These loads and deformations define structural requirements. As we are designing a fleet of vehicles, we must consider the loading of the population of vehicles and set the required capacity not at that of a typical vehicle but for that small fraction of vehicles which will experience an extreme or severe level of loading, Figure 2.7b. Precisely where to set the load requirement between reasonable but extreme loading and abusive loading is subjective.

A four-step process is used to identify requirements for the *locate and retain* function. After selecting a specific subsystem for analysis,

1. Choose a mode-of-use for the subsystem
2. Identify the loads being applied to the subsystem during this mode
3. Identify how much deformation of the structure is allowable without a detrimental effect on functioning for this mode
4. Using free-body analysis, determine the loads applied at the structure interfaces.

The implementation of this process is best understood using some examples.

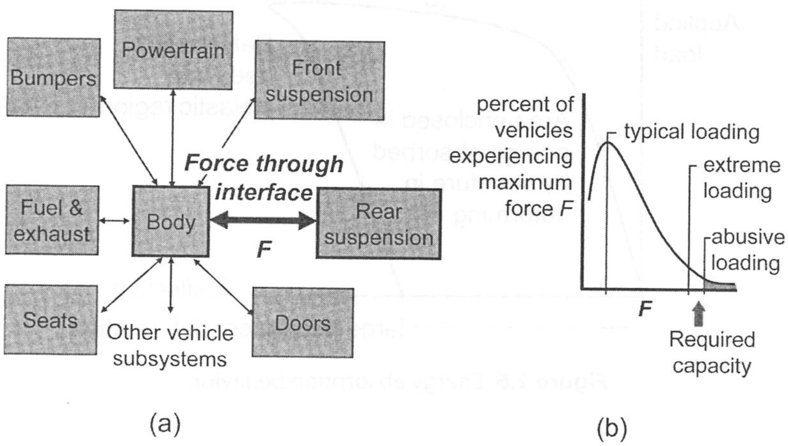

Figure 2.7 Body – subsystem interfaces.

For these two modes, the *entry/exit mode* provides the dominant strength requirement (*1500 N*), and the *column vibration mode* provides the dominant stiffness requirement (*240 N/mm*), Figure 2.8. To complete development of structural requirements for the steering column mount, other modes would be analyzed including *driver toggle arms, crash impact loading*, etc.

Example: Powertrain mounting structure

The powertrain mounting structure in a front-wheel-drive vehicle locates and retains the engine and transmission, usually at three to four mounting locations on the body structure. Example modes which provide dominant structural requirements include *stall torque* and *vibration isolation*, Figure 2.9.

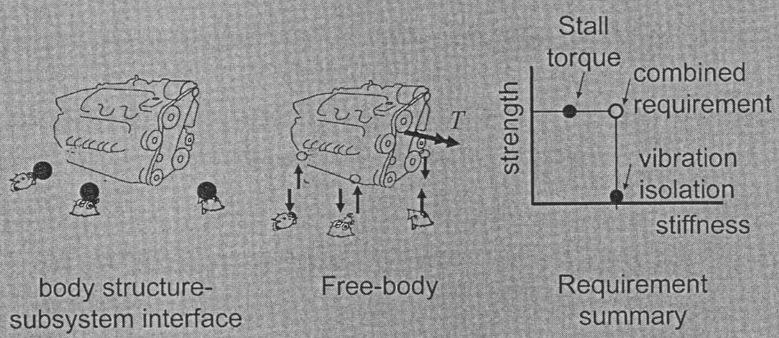

Figure 2.9 Powertrain mount.

1. *Mode of use:* stall torque.
2. *Load being applied*: During stall torque, the maximum torque the powertrain can generate is applied at the drive shafts and is reacted at the mounting points.
3. *Allowable deformation*: In this strength requirement, a small amount of permanent deformation (approximately *2 mm*) is acceptable.
4. *Loads at structure interfaces*: For a particular mount geometry, the strength requirement at each mount point may be found by static equilibrium of the powertrain, Figure 2.9.

For the vibration isolation mode, we are interested in minimizing the transmission of vibratory forces from the engine.

1. *Mode of use*: vibration isolation.
2. *Load being applied:* The applied loads are very small.
3. *Allowable deformation*: Ensure the ability to tune the mount rate to minimize transmitted engine vibration. This is done when the deflection of the structure is less than *0.1* to *0.14* times the deflection across the mount. This translates into a required stiffness which is *7-10* times that of the elastomeric engine mount rate.
4. *Loads at structure interfaces:* We can find the required stiffnesses at the structure interfaces using a free body as shown in Figure 2.9.

Example: Steering column mount structure

The steering column mount structure locates and retains the steering column, Figure 2.8. It performs this function in several modes of use including *entry/exit* and *column vibration.* Below we analyze each of these modes to determine structural requirements.

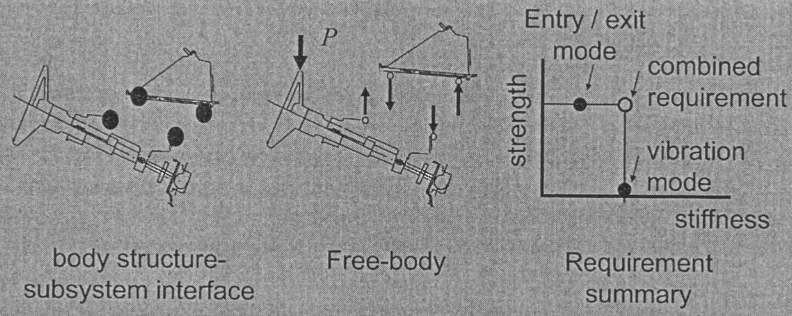

Figure 2.8 Steering column mount.

1. *Choose a mode-of-use for the subsystem:* To aid entering and exiting the vehicle, the driver often grasps the steering wheel and applies a vertical load.
2. *Identify the loads being applied to the subsystem during this mode*: For a large person, this load is approximately *1500 N.*
3. *Identify how much deformation of the structure is allowable without a detrimental effect on functioning for this mode*: The driver would not be distressed if the column deflects elastically up to *10 mm* under this load (a required stiffness of *150 N/mm*) but would be distressed if a noticeable permanent deformation larger than *1 mm* remained (a required strength of *1500 N*).
4. *Using free-body analysis, determine the loads applied at the structure interfaces*: Figure 2.8 shows a free-body for this case.

So in this mode, we determine a requirement for strength of *1500 N* and a requirement for stiffness of *150 N/mm*. Now consider another mode of use: column vertical vibration. The column mount structure and column form a vibratory system, with the structural mount providing stiffness and the column providing inertia.

1. *Mode of use*: Column vertical vibration.
2. *Load being applied*: The applied loads are very small and are significant only when at the resonance frequency of the mounted column.
3. *Allowable deformation*: It is desirable for this system to have a resonance of at least *35 Hz* to avoid coupling with powertrain excitation at engine idle. Based on the relationship $k=m\omega_n^2$, and with the steering column effective mass of *5 kg*, a mount stiffness requirement of *240 N/mm* results. (Structure vibration will be more fully discussed in a later chapter.)
4. *Loads at structure interfaces*: We can find the required stiffnesses at the structure interfaces using a free body as shown in Figure 2.8.

For these two modes, the *stall torque mode* provides the dominant strength requirement and the *vibration isolation mode* provides the dominant stiffness requirement, Figure 2.9. To complete development of structural requirements, other modes would be analyzed such as *engine retention during low-speed impact.*

2.3 Locate and Retain for Front Suspension Attachment Structure

The front suspension attachment structure, Figure 2.10, locates and retains the suspension at several points: the shock absorber, spring, and control arm. Example modes which provide dominant structural requirements include *braking, cornering, rollover, vertical bump, vibration isolation,* and *handling*. The first four modes define strength requirements, and the last two, stiffness requirements.

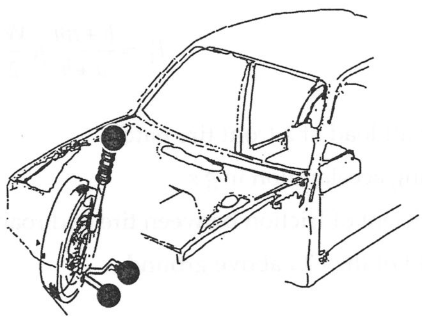

Figure 2.10 Suspension attachment.

1. *Modes of use*: braking, cornering, rollover, and vertical bump.
2. *Loads being applied:* In this analysis, we first look at the maximum loads at the tire patch during these modes, and then using static equilibrium of the suspension, determine the maximum loads (strength requirements) at the body attachment points.

The vehicle at rest is shown in Figure 2.11. Using static equilibrium, the front and rear tire patch loads, R_F and R_R, may be determined as

$$R_F = \frac{b}{a+b}W \quad \text{and} \quad R_R = \frac{a}{a+b}W \qquad (2.1)$$

where:

R_F = Vertical load at a front tire patch

R_R = Vertical load at a rear tire patch

W = Vehicle weight

a, b = Dimensions shown in Figure 2.11

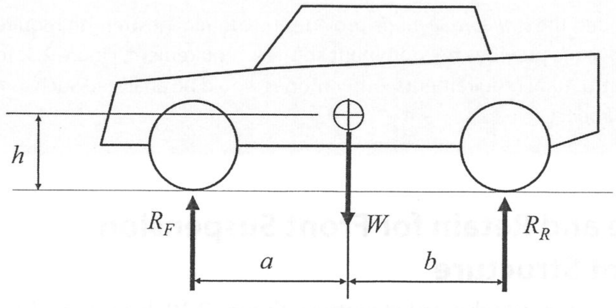

Figure 2.11 Vehicle at rest: Front tire patch load.

Now consider a steady-state braking deceleration of n times the acceleration due to gravity, Figure 2.12. Again using static equilibrium, the fore-aft load at the tire patch is

$$F_F = \frac{b+nh}{a+b}\mu\frac{W}{2} \tag{2.2}$$

where:

F_F = Fore-aft load at a front tire patch

n = Braking acceleration in g's

μ = Coefficient of friction between tire and road

h = Height of the CG above ground

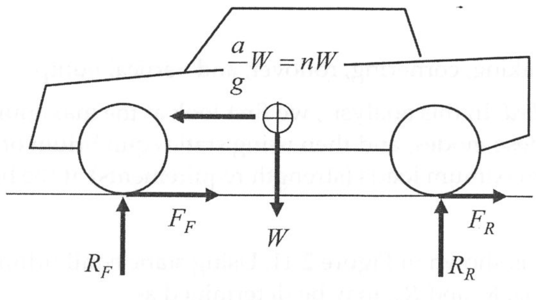

Figure 2.12 Vehicle braking: Front tire patch load.

For the same vehicle we now look at cornering loads at the tire patch, Figure 2.13. The steady-state lateral cornering acceleration is given by n in g's. Considering the front axle free body, the lateral load on the outer tire is:

$$L_O = \mu\left(\frac{1}{2}+\frac{hn}{t}\right)\left(\frac{b}{a+b}\frac{W}{2}\right) \tag{2.3}$$

where:

L_O = Lateral load on the outside front tire patch

W = Vehicle weight

t = Track width

Other variables are listed under Equations 2.1 and 2.2.

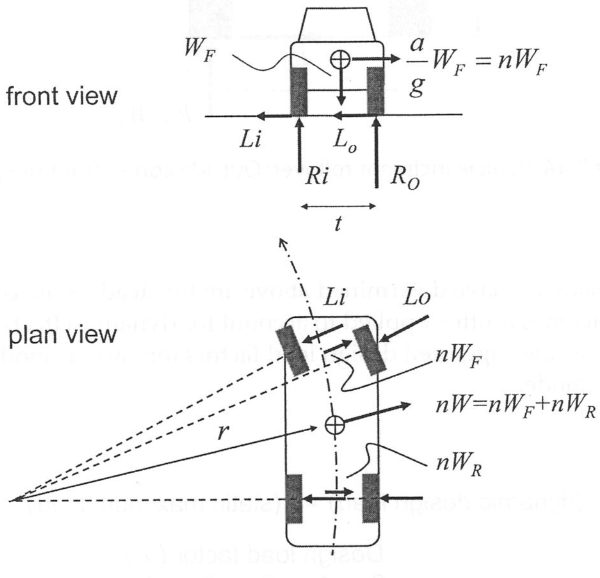

Figure 2.13 Vehicle cornering: Outside corner front tire patch load.

When rollover of the vehicle is incipient during cornering, the steady-state resultant acceleration at the center of gravity (CG) begins to go outside the base of the vehicle track, Figure 2.14. This occurs when the lateral acceleration in *g's* is $n=t/(2h)$, then the lateral tire patch load at the front axle is

$$L_O = \frac{2h}{t}\left(\frac{b}{a+b}\frac{W}{2}\right) \tag{2.4}$$

where:

L_O = Lateral load at the tire patch

W = Vehicle weight

h = Height of CG above ground, shown in Figure 2.14

t = Vehicle track

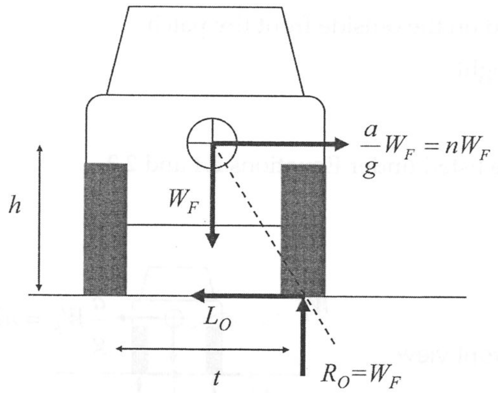

Figure 2.14 Vehicle incipient rollover: Outside corner front tire patch load.

Because the loads we have determined above are for steady-state conditions, a design load factor, *r*, is often applied to account for dynamic effects [5, 6]. Figure 2.15 summarizes the suggested design load factors for various modes including the vertical bump mode.

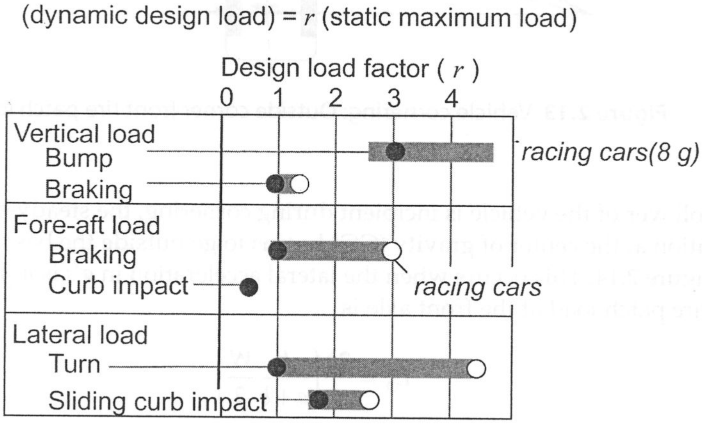

Figure 2.15 Dynamic load factors.

The maximum front tire patch loads for these modes are summarized in Figure 2.16. The steady-state maximum for each of these modes is taken to occur when the braking and cornering acceleration is $n=1$, and the coefficient of friction between tire and road is $\mu=1$. Again looking at Figure 2.16, the maximum lateral, fore-aft, and vertical loads are the greatest considering all modes. For lateral loads this is the rollover mode, for fore-aft it is the braking mode, and for vertical it is the *3-g* bump mode.

Mode	Lateral	Fore-aft	Vertical
static	——	——	$R_F = \left(\frac{b}{a+b}\right)\frac{W}{2}$
braking	——	$F_F = \mu\left(\frac{b+nh}{a+b}\right)\frac{W}{2}$	$R_F = \left(\frac{b+nh}{a+b}\right)\frac{W}{2}$
cornering	$L_O = \mu\left(\frac{1}{2}+\frac{nh}{t}\right)W_F$	——	$R_O = \left(\frac{1}{2}+\frac{nh}{t}\right)W_F$
incipient rollover	$L_O = \left(\frac{2h}{t}\right)W_F$	——	$R_O = W_F$
max acceleration coefficient of friction dynamic load factor	$n = 2h/t$ (rollover) $\mu = 1$ $r = 1$	$n = 1$ (1g braking) $\mu = 1$ $r = 1$	$n = 1$ $\mu = 1$ $r = 3$ (3g bump)
design load per tire (max of all the above)	$L_O = \left(\frac{2h}{t}\right)W_F$	$F_F = \left(\frac{b+h}{a+b}\right)\frac{W}{2}$	$R_F = 3\frac{W_F}{2}$

For each design load, allowable deflection is on-set of permanent deformation

Figure 2.16 Summary: Front tire patch loads.

3. *Allowable deformation*: For all modes, the allowable deformation of the structure is that which could be compensated for by a suspension realignment (about *1–2 mm* of permanent deformation).
4. *Loads at structure interfaces*: With these maximum loads identified at the tire patch, we can now use static equilibrium of the suspension to determine the maximum loads at the structure interfaces, Figure 2.17. Here we consider a highly idealized McPherson strut front suspension with a horizontal lower control arm, and we determine the maximum loads at the lower control arm attachment in the vertical, lateral, and fore-aft directions, A_V, A_L, A_{FA}, and similarly for the strut attachment, S_V, S_L, S_{FA}.

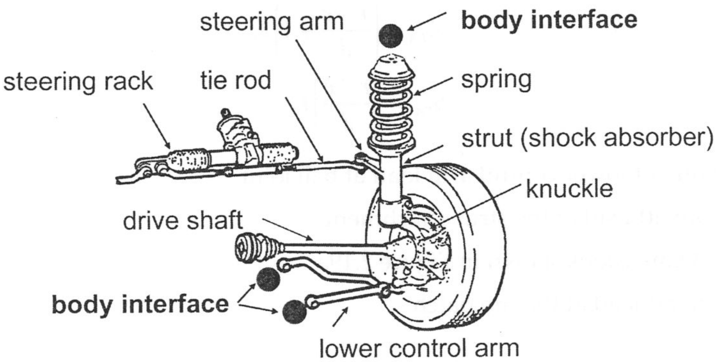

Figure 2.17 Suspension – body interfaces.

For the maximum lateral tire patch load during rollover mode, Figure 2.18:

$$A_L = \left(\frac{r-c}{d}+1\right)L_0$$
$$S_L = \left(\frac{r-c}{d}\right)L_0 \qquad (2.5)$$

where:

A_L = Lateral lower control arm load at the body attachment

S_L = Lateral load at the strut attachment

r, c, d = Dimensions shown in Figure 2.18

L_O = Lateral load at the tire patch

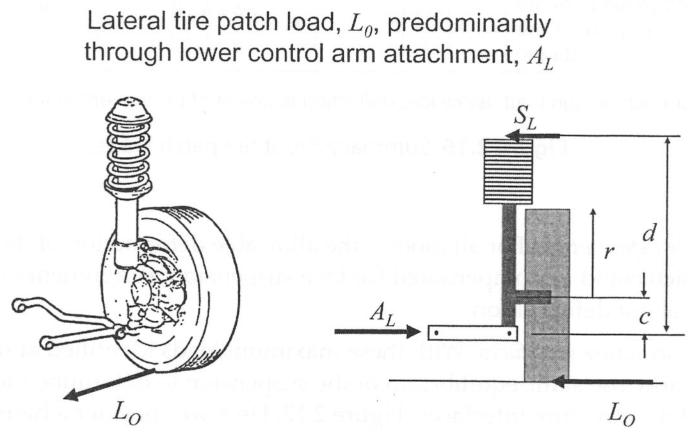

Figure 2.18 Suspension lateral loading.

For the maximum fore-aft tire patch load during braking mode, Figure 2.19a, the loads at the lower control arm ball joint are:

$$A_{FA} = \left(\frac{r-c}{d}+1\right)F_F$$
$$S_{FA} = \left(\frac{r-c}{d}\right)F_F \qquad (2.6)$$

where:

A_{FA} = Fore-aft lower control arm load at ball joint

S_{FA} = Fore-aft load at the strut attachment

r, c, d = Dimensions shown in Figure 2.19a

F_F = Fore-aft load at the tire patch

Fore-aft tire patch load, F_F, predominantly through lower control arm ball joint, A_{FA}

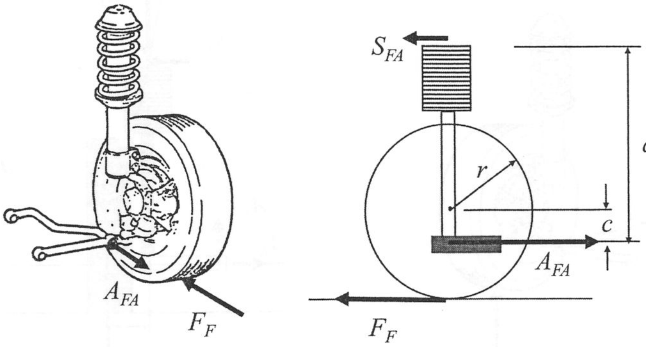

Figure 2.19a Suspension fore-aft loading at ball joint.

These ball joint loads are reacted at the lower control arm front and rear bushings, Figure 2.19b, with the specific breakdown of loads depending on the relative bushing stiffness. Often, one of the bushings is designed to be very stiff and take most of the fore-aft load applied at the ball joint as shown in Figure 2.19b.

Reaction of lower control arm ball joint load, A_{FA}, at lower control arm attachment

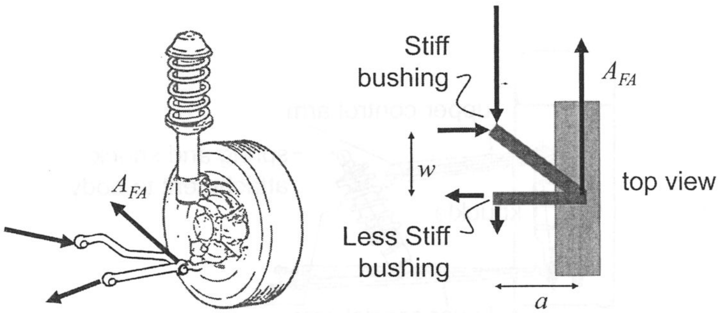

Figure 2.19b Suspension fore-aft loading at lower control arm attachment.

For the maximum vertical tire patch load during bump mode, Figure 2.20:

$$\begin{aligned} A_V &= 0 \\ S_V &= R_F \end{aligned} \tag{2.7}$$

where:

A_V = Vertical lower control arm load at body attachment

S_V = Vertical load at the strut attachment

R_F = Vertical load at the tire patch

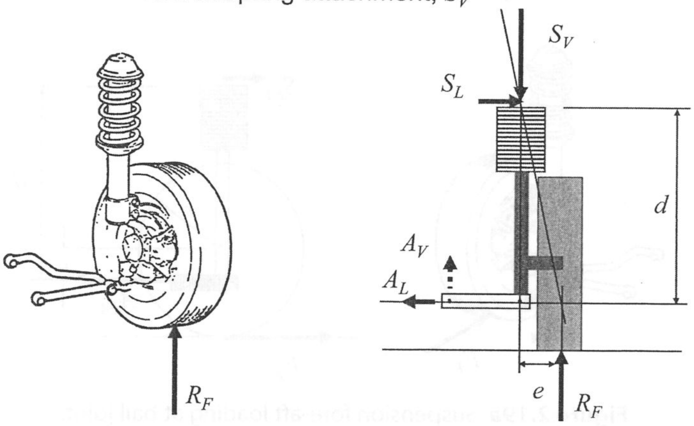

Figure 2.20 Suspension vertical bump load.

Numerical values for these loads become the strength requirements for the respective body structure interfaces. Note that the above maximum load requirements for body structure are for the specific suspension type shown in Figure 2.17. Other types will have different maximum loads applied to the body given the same tire patch loads. For example, an alternative suspension geometry is the Short-and-Long-Arm (SLA) suspension shown in Figure 2.21.

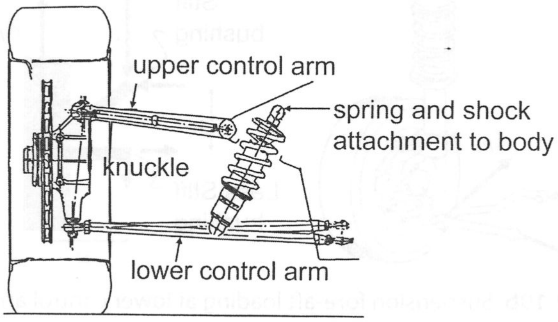

Figure 2.21 Short-and-long-arm suspension.

Looking, for example, at the maximum vertical load at the spring-shock attachment during a bump, we find, Figure 2.22:

$$A_V = \left(\frac{1}{\lambda} - 1\right) R_F$$
$$S_V = \frac{1}{\lambda} R_F \tag{2.8}$$

where:

A_V = Vertical lower control arm load at body attachment

S_V = Vertical load at the spring/shock attachment

λ = Lever ratio for the spring/shock attachment to lower control arm

R_F = Vertical load at the tire patch

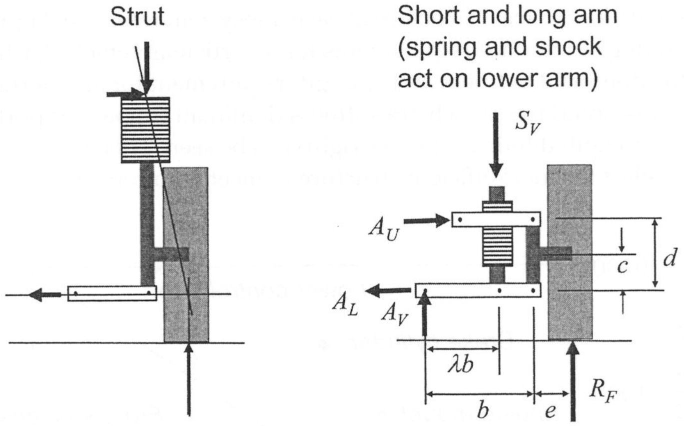

Figure 2.22 Vertical bump load for SLA suspension.

Thus, for a typical SLA lower control arm with lever ratio of $\lambda=0.7$, the spring-shock maximum loads are 1.4 times that of a McPherson strut, Figure 2.23.

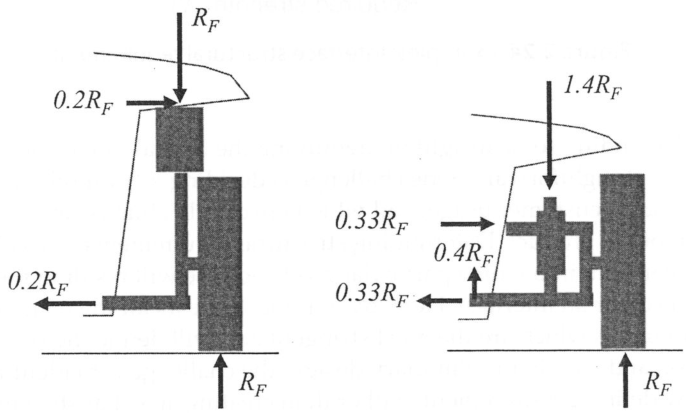

Figure 2.23 Comparison of loads: Strut and SLA suspensions.

The above analysis resulted in strength requirements at the suspension interfaces. For stiffness requirements we look to the *vibration isolation mode*. We would like seven to ten times the suspension bushing stiffness at each structure interface. With structure stiffness at this ratio, effective tuning of the bushing is enabled and also effective utilization of the bushing's damping qualities, as will be developed in the chapter on vibration.

Interfaces for other vehicle subsystems may be analyzed in a similar way to provide the requirements for the local structure at each subsystem interface. Figure 2.24 shows a sampling of interface requirements for a particular vehicle. Each point represents the dominant stiffness and strength requirement for an interface. Shown in this way, those interfaces which are stiffness dominant (upper left portion) and those that are strength dominant (lower right) can be seen. This distinction will be used later to select the most efficient structure to meet requirements.

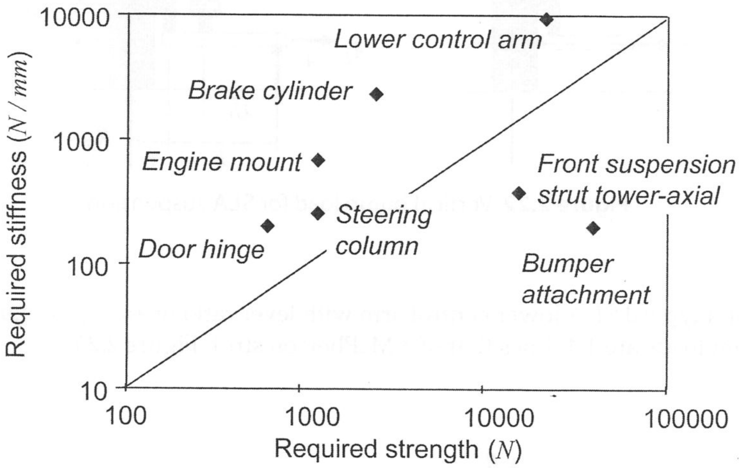

Figure 2.24 Examples: Interface structural requirements.

Although demanding some insight in identifying the critical modes-of-use, this process is straightforward. One challenge is deciding what modes are within reasonable customer usage, and which are clearly abusive and beyond the function of the product. Determining structural requirements also calls for considerable insight into which particular modes-of-use will result in the dominant requirement set for an interface. Here, by dominant, we mean the relatively small set of requirements which are the most stringent and will define the structure configuration and size. For preliminary design, the challenge is to identify the precious few defining requirements rather than creating an exhaustive list. Generally, the interfaces which define body load paths are those of the suspension and powertrain; influence of other interfaces is localized.

Although *locate and retain* addresses a very basic and important function of the body structure, there are other global structural requirements which must be met for a refined vehicle. To define these additional requirements we need to look at overall vehicle functions and see what role the body structure must play for those functions.

2.4 Flow Down of Requirements from Vehicle-Level Functions

A foundational principle of systems analysis can be stated as follows: to understand a system, one must look at the role it plays in the larger system which contains it, Figure 2.25 [7]. The system we would like to understand is the automobile body structure, so we must determine its role in making the larger containing system—the vehicle—successful, Figure 2.26. Many of the vehicle functions impose some needed structural performance from the body. To develop structure requirements then, we analyze the role the body structure plays in each of the functions which the vehicle provides, Figure 2.27.

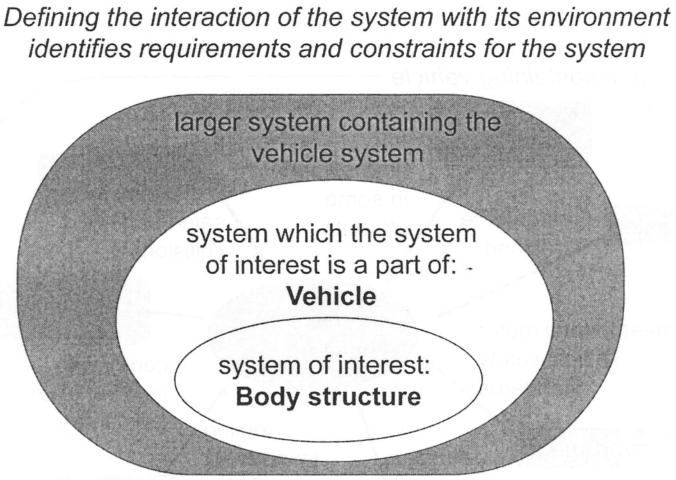

Figure 2.25 Expanding system boundaries.

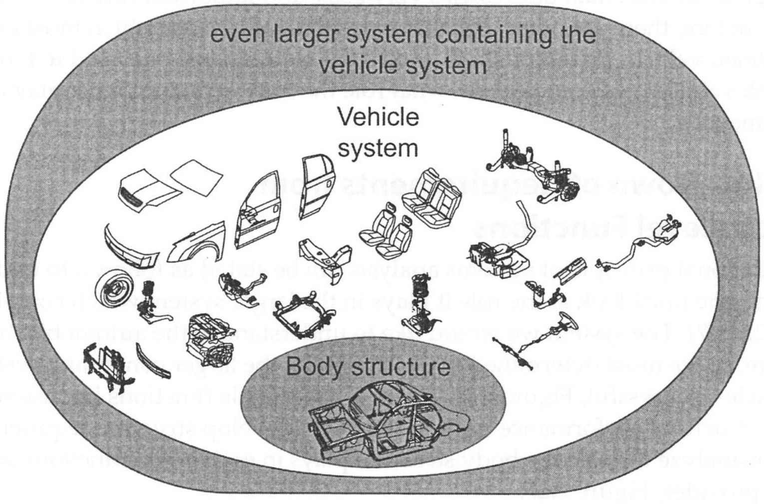

Figure 2.26 Automobile system boundaries.

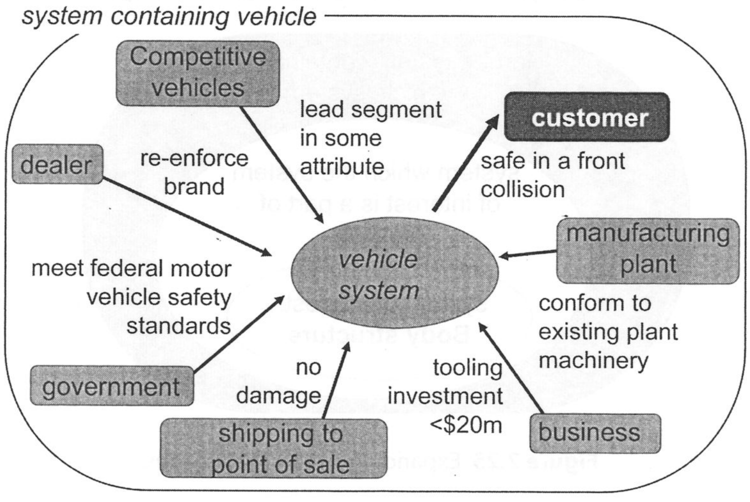

Figure 2.27 Some functions performed by vehicle.

Figure 2.28 lists many of the vehicle functions satisfying customer needs. The body structure plays an important role in achieving the functions of *noise and vibration, ride and handling, durability, safety, styling, energy use, package, human factors,* and *thermal environment*. Besides these functions directed at the ultimate customer, the vehicle interacts with many other entities and must also satisfy constraints from the manufacturing plant, government, dealer network, business financials, shipping, etc.

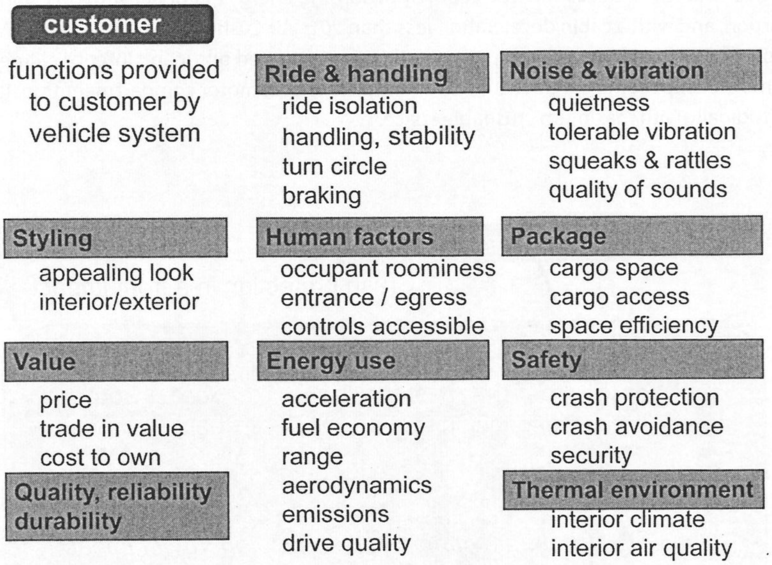

Figure 2.28 Functions supporting the customer.

By analyzing the role the body structure must play in satisfying each of these entities, we determine the functional requirements and constraints. The steps for this analysis are:

1. Identify the vehicle function to be accomplished.
2. Define how the vehicle subsystems will work together to provide that function—*function strategy*. This working together often includes a sharing of the applied loads between subsystems. Such load sharing can increase mass efficiency. An example of load sharing is given in the following example.
3. Analyze the role of the body structure in accomplishing the strategy (that is, define loads and allowable deflections in the categories of stiffness, strength, and energy absorption).
4. Flow down the overall body structure requirements to requirements on the structural subsystems and elements.

Example: Front impact structural requirements

Consider the vehicle-level function of safety in a front impact.

1. *Identify the vehicle function to be accomplished:* In this case, we will focus on minimizing injury in a *30 mph* front barrier.
2. *Define how the vehicle subsystems will work together to provide that function—function strategy:* To provide this function, a particular vehicle system strategy is defined, Figure 2.29. An example of such a strategy is: Decelerate the cabin by absorbing energy of impact with no cabin distortion, and with a cabin deceleration less than *20 g*. Air Cushion Restraint System (ACRS) deploys at *10 msec*, with optimal spatial relationship to seated occupant. Interior elements which the occupant may impact are crushable. Elements in motor compartment translate longitudinally with maximum crushable space.

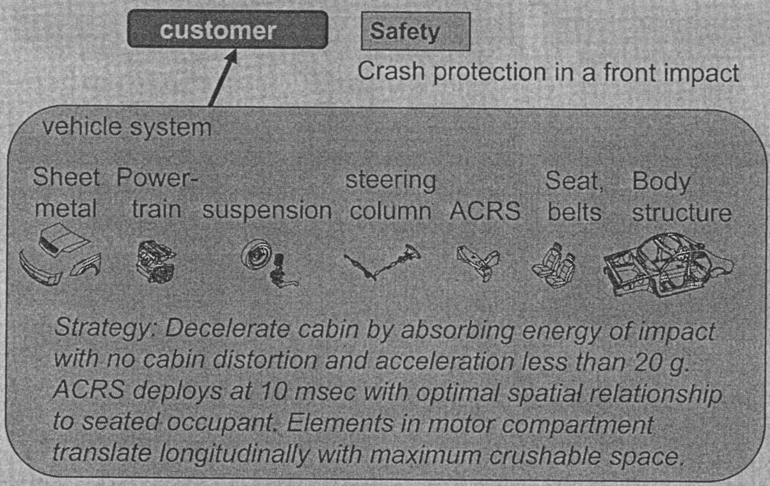

Figure 2.29 Strategy for crash protection in a front impact.

3. *Analyze the role of the body structure in accomplishing the strategy (that is, define loads and allowable deflections in the categories of stiffness, strength, and energy absorption):* To meet this strategy, several vehicle subsystems must work together in a coordinated way. These include the front-end sheet metal, front suspension and wheels, powertrain, steering column, ACRS, seat, and body structure, Figure 2.30. For example, applied barrier loads will be shared by the body structure and powertrain.

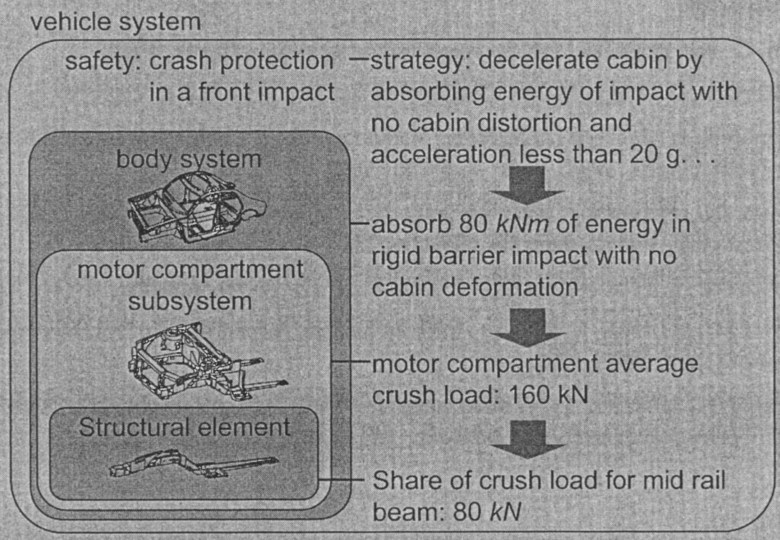

Figure 2.30 Vehicle requirements flow down to body structure requirements.

Now consider the role of the body structure in this strategy. It is one of the subsystems which will decelerate the cabin by absorbing energy of impact with no cabin distortion, and with a cabin deceleration less than *20 g*. From this, we can determine the amount of energy to be absorbed by the body structure using basic physics. This results in a body structure requirement in the energy-absorbing category, Figure 2.29.

4. *Flow down the overall body structure requirements to requirements on the structural subsystems and elements:* We can then flow this body requirement down to a structural subsystem requirement for the motor compartment, Figure 2.30 – the average load to be generated as the compartment crushes. We can further flow this *structural subsystem* requirement to a *structural element* requirement for the midrail beam – the average crush load for that beam.

We now have a procedure for identifying structural requirements based on vehicle functions. Applying this procedure to a particular vehicle will result in a large number of requirements and, as was the case for the locate-and-retain function, we again look for that small set of requirements which define the structure topology. We will suggest that small set as we discuss design for bending, torsion, crashworthiness, and vibration in subsequent chapters. In preparation for that, in the next chapter we will look at the behavior of the body structural elements.

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