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Introduction

Automobiles have been used for over 100 years for the transportation of people and goods. Despite this long period, essential elements of an automobile have in principle remained the same, i.e. four wheels and an internal combustion engine with a torque converter drive. However, the technical details of an automobile have changed a great deal, and the complexity has increased substantially. This has partly gone hand in hand with general technical progress, on the one hand, and increasing customer demands, on the other. Legal requirements have also led to distinct changes in automobiles.

The importance of automobiles becomes evident when we look at the graphs in Figures 1.1–1.4. You should bear in mind that the abscissas of most graphs are partitioned logarithmically. The quantity, the distances travelled and the distances travelled per capita are at a very high level, or these values are increasing at a high rate. If we look at some European countries or the United States of America, we can recognize stagnation at a high level, whereas emerging economies exhibit high rates of growth. The need to develop new, economic and ecological vehicles is evident. In order to do this, engineers should be familiar with the basic properties of automobiles. As the automobile is something which moves and which not only moves forward at a constant velocity, but also dynamic behaviour depends on these basic properties. Consequently, the basic dynamic properties form the main topic of this book.

The ecological aspect could be a dramatic limiting factor in the development of vehicles throughout the world. If the number of cars per 1000 inhabitants in China and Hong Kong grows from 22 in the year 2007 to 816, which is the number in the USA, then this represents a factor of 40. If we now multiply the CO_2 emissions of the USA from the year 2007 by 40, we obtain around 57 000 Mt, which is 12 times the world CO_2 emissions from fuel combustion in road transport for the year 2007. This seems to be very high (or perhaps too high), and vehicles with lower fuel consumption or hybrid or electric powertrains will have to be developed and improved in the coming decades.

Vehicle Dynamics, First Edition. Martin Meywerk.

Companion Website: www.wiley.com/go/meywerk/vehicle

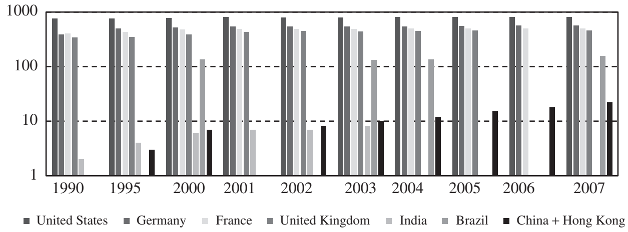

Figure 1.1 Passenger cars (and light trucks in US) per 1000 inhabitants (data from OECD 2014)

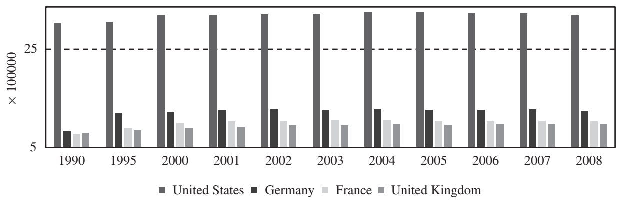

Figure 1.2 Road passenger km (million pkm) (data from OECD 2014)

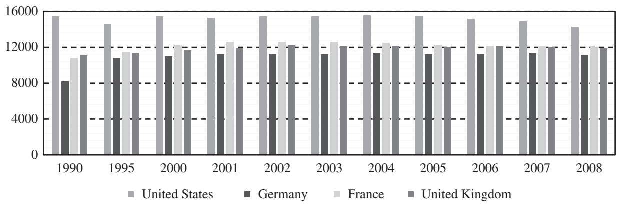

Figure 1.3 Passenger km/capita (data from OECD 2014)

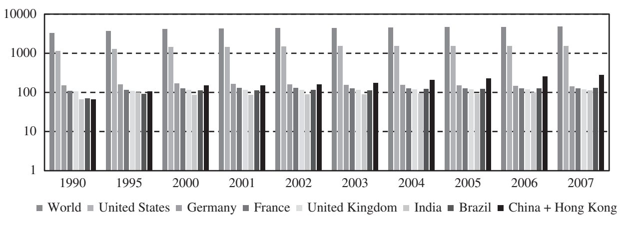

Figure 1.4 International Energy Agency (IEA) CO_2 from fuel combustion (Mt) in Road Transport (data from OECD 2014)

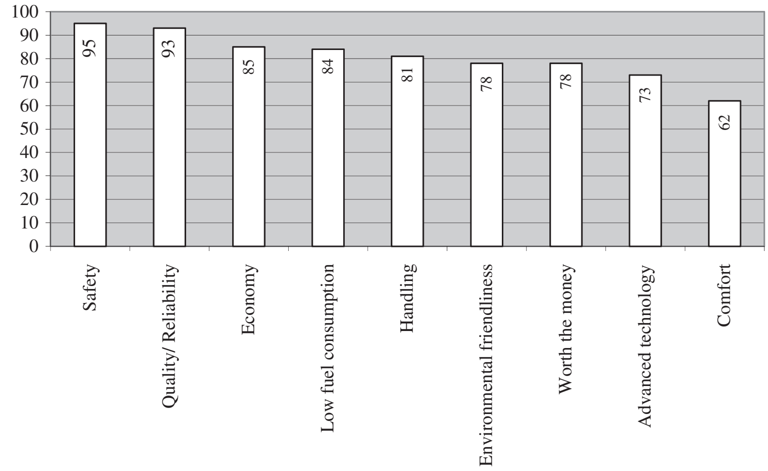

Figure 1.5 Importance of purchase criteria (Braess and Seiffert 2001)

The presentation of the most important buying criteria in Figure 1.5 highlights the ecological and economic aspects as well as safety, handling behaviour and comfort. The last three points, namely safety, handling behaviour and comfort, are strongly linked with the driving dynamics and suspension, making these aspects of particular importance in the automotive industry. Safety is generally subdivided into active safety (active safety systems help to avoid accidents) and passive safety (passive safety systems protect the occupants during an accident).

It is evident that the dynamics of the vehicle is of crucial importance because of the impact on active safety; handling behaviour and comfort are also closely associated with the properties of vehicle dynamics. For this reason, particular emphasis is placed on the aspect of dynamics in this course.

The aim of this course is to define and identify the basic concepts and relationships that are necessary for understanding the dynamics of a motor vehicle.

The content of this textbook is limited to the essentials, and the course closely follows the monograph of Mitschke and Wallentowitz 2004 (German). Further recommended reading can be found in the bibliography at the end of this book, e.g. Heissing and Ersoy 2011, Dukkipati et al. 2008, Gillespie 1992, Jazar 2014, or Reimpell et al. 2001.

1.1 Introductory Remarks

The content of this book is divided into four parts: longitudinal dynamics, vertical dynamics, lateral dynamics and structural design of vehicle components and automotive mechatronic systems. Longitudinal dynamics is included in Chapters 2–6, which discuss the process of acceleration and braking. Key importance here is given to the total running resistance, the demand and supply of power and the driving state diagrams. In Chapters 7 and 8, additional systems of longitudinal dynamics are described: alternative powertrains and adaptive cruise control systems. In Chapters 9 and 10, the behaviour of the vehicle when driving on an uneven surface is explained in the context of vertical dynamics. These chapters study the basics of the theory of oscillations and the influence of vibrations on humans. Lateral dynamics, the contents of Chapters 11–15, describes the handling behaviour of a vehicle during cornering. Important concepts such as slip, oversteer and understeer, toe and camber angle are explained. It deals with the influence of wheel load on the handling behaviour.

Chapters 16–19 highlight the engineering design (structural) aspects of an automobile. In addition to speed and torque converters, they also discuss brakes and chassis elements of active safety systems, such as anti-lock braking system (ABS), anti-slip regulation (ASR) and electronic stability programme (ESP). In Chapter 20, multi-body systems (MBS) are explained. MBS are computational models which allow more precise calculations of the dynamic behaviour of vehicles.

1.2 Motion of the Vehicle

To describe the dynamics of motor vehicles, we use, as in any other branch of engineering, models with a greater or lesser degree of detail. The complexity of the models depends on the questions under investigation. Today the MBS models are most commonly used in both science and research as well as in the development departments of the automotive industry. Multi-body systems consist of one or more rigid bodies which are interconnected by springs and/or shock absorbers and joints.

Figure 1.6 shows an MBS model of a vehicle. This model is taken from the commercial MBS programme ADAMS. Another example of a McPherson front axle is shown in Figure 1.7. These MBS models allow high accuracy in the simulation of dynamic behaviour. A lot of details can be incorporated into these models, even flexible parts can be considered. However, the detailed simulation yields a large number of effects in the calculated results and the engineer has to interpret and understand these results. As an example, an engineer has to distinguish between main effects and numerical phenomena. For this purpose, it is helpful to understand the basic dynamics and to know simple models for calculating the behaviour of a vehicle in order to interpret or even to check the MBS results. This book therefore takes vehicle dynamic behaviour and simple models as its main topics.

In a simplified view of the motor vehicle, a model could consist of five rigid bodies: the four wheels and the body structure. These are interconnected by springs, shock absorbers and rigid body suspensions with joints. A rigid body has six degrees of freedom. This simple model would therefore have $5 \times 6 = 30$ degrees of freedom[1].

[1] We may argue that the suspension between wheel carrier and body of the vehicle locks five degrees of freedom, the wheel bearing will unlock one degree of freedom, which results all together in only two degrees of freedom for one wheel. The sum for the whole vehicle will then be 14. That is correct under the assumption that there are no compliances in the suspension. Since modern cars have these compliances, the number of 30 is correct.

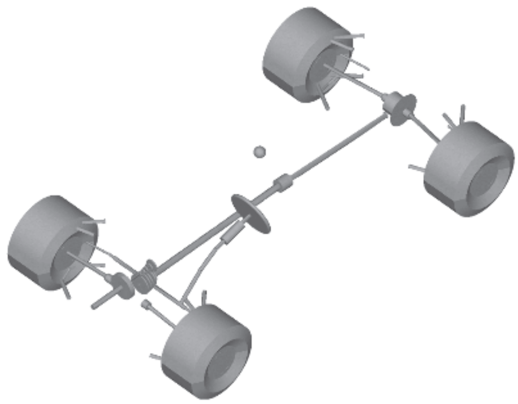

Figure 1.6 MBS model of a four-wheel-drive vehicle (example of the MBS programme ADAMS)

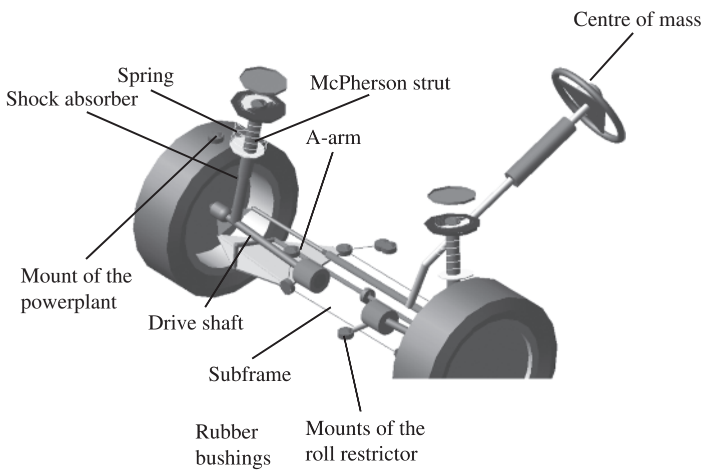

Figure 1.7 McPherson front axle with driven wheels (from MBS programme ADAMS)

It is evident that a description of even this simple model with 30 degrees of freedom will require 30 equations of motion of second order (with respect to time).

Equations of motion are ordinary differential equations that describe the motion of (rigid) bodies. A simple example of the equation of motion for a single mass oscillator is given below (mass m, stiffness of spring k, displacement z):

$$m\ddot{z} + kz = 0\ . \tag{1.1}$$

Equations of motion are often second-order differential equations with respect to time. For specific problems, these models are therefore reduced to a few masses with limited motion options. Hence, we in turn limit ourselves to certain specific questions. This approach will be used in this book. For this reason, we first introduce the terminology and coordinates to describe the possible motions of a vehicle.

Frame system: A quadruple $(A, \vec{e}_x, \vec{e}_y, \vec{e}_z)$ is a frame system of an affine space. Here, A is a point (the origin) and $\vec{e}_x, \vec{e}_y, \vec{e}_z$ is a Cartesian tripod (the axis system). To describe the position of a point P with respect to A, three coordinates x, y, z are sufficient:

$$\overrightarrow{AP} = x\vec{e}_x + y\vec{e}_y + z\vec{e}_z \ . \tag{1.2}$$

The point A can be defined as fixed in space (or in an inertial frame). This is called an inertial frame system (sometimes called earth or world coordinate system). If the point A and the tripod $\vec{e}_x, \vec{e}_y, \vec{e}_z$ are fixed to a body and continues to be firmly connected to the body then the result is called a body-fixed frame system.

We introduce several frames. The first one is an inertial frame $(O, \vec{e}_{ix}, \vec{e}_{iy}, \vec{e}_{iz})$ which is fixed to the earth (or the world)[2]. To describe the motion of a point in this inertial frame, three Cartesian coordinates x, y, z are necessary, in the case of the centre of mass, S_{cm}, of the vehicle we introduce x_v, y_v, z_v. This point S_{cm} is the origin for two other, fixed body frame systems for the vehicle:

1. $(S_{\text{cm}}, \vec{e}_{vx}, \vec{e}_{vy}, \vec{e}_{vz})$: vehicle frame system
2. $(S_{\text{cm}}, \vec{e}_x, \vec{e}_y, \vec{e}_z)$: intermediate frame system

The first one is completely fixed to the body of the vehicle, i.e. all three vectors $\vec{e}_{vx}$, $\vec{e}_{vy}$, $\vec{e}_{vz}$ move together with the vehicle. The origin of the second is also fixed to the vehicle. To define the intermediate frame system, we assume only a rotation about the $\vec{e}_{iz}$ direction, this means that $\vec{e}_{iz} = \vec{e}_z$. Then the vector $\vec{e}_x$ is the vector $\vec{e}_{ix}$ rotated by the so-called yaw angle, ψ, about the $\vec{e}_{iz}$ direction. The vector $\vec{e}_y$ is oriented to the left side of the vehicle, perpendicular to $\vec{e}_x$ and parallel to the $\vec{e}_{ix} - \vec{e}_{iy}$ plane. The vector $\vec{e}_z = \vec{e}_x \times \vec{e}_y$ is the vector or cross product[3].

In order to define the orientation of the vehicle and the orientation of the axis system, $\vec{e}_{vx}$, $\vec{e}_{vy}$, $\vec{e}_{vz}$, with respect to the inertial axis system, $\vec{e}_{ix}$, $\vec{e}_{iy}$, $\vec{e}_{iz}$, three angles are necessary. There are different ways to use these three angles: here we use the Euler (see footnote) convention. This means that we first rotate about the $\vec{e}_{iz}$-axis; the angle for this first rotation is the yaw angle, ψ. After this, we rotate about the new $\vec{e}^{\,\prime}_{iy}$-axis (which is the rotated $\vec{e}_{iy}$-axis from the first rotation); the angle for this second rotation is the pitch angle, ϑ. The third rotation is about the new $\vec{e}^{\,\prime\prime}_{ix}$-axis. The $\vec{e}^{\,\prime\prime}_{ix}$-axis is the

[2] In some MBS software tools this coordinate system is called world system. Strictly speaking, an earth frame system, i.e. a coordinate system which is fixed to the earth, is not an inertial system due to the rotation of the earth. These aspects are usually neglected, as is the case here as well.

[3] If the coordinates of two vectors with respect to an orthonormal basis are (x_1, y_1, z_1) and (x_2, y_2, z_2), then the vector product can be calculated by $(y_1 z_2 - y_2 z_1, -(x_1 z_2 - x_2 z_1), x_1 y_2 - x_2 y_1)$.

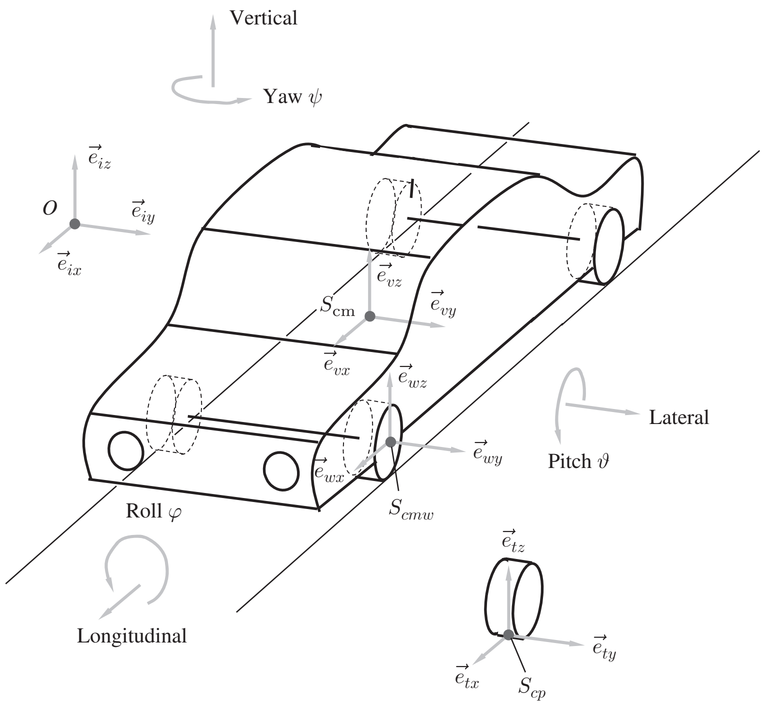

Figure 1.8 Motion of a vehicle

result from the $\vec{e}_{ix}$-axis due to the two rotations with the angles ψ and ϑ. The angle of the third rotation is the roll angle[4] φ.

Some more frame systems are necessary to describe the motion of the vehicle. Figure 1.8 depicts a frame system, $(S_{cmw}, \vec{e}_{wx}, \vec{e}_{wy}, \vec{e}_{wz})$, fixed to the wheel at its centre of mass and an additional system at the contact patch, $(S_{\mathrm{cp}}, \vec{e}_{tx}, \vec{e}_{ty}, \vec{e}_{tz})$.

Figure 1.8 shows the frame systems and the angles ψ, ϑ and φ. The angles are not depicted as angles of a sequence of rotations, but as angles of single rotation. This simplification is made in several considerations of this book. For most of them, it is sufficient to look at a single rotation and neglect the interaction of rotation. If the interactions of the rotations are to be investigated, the complexity of the equations will increase significantly. Simple, analytical results are not available for these investigations and the motion of the vehicle should be modelled by MBS.

[4] These three angles are called the Tait–Bryan angles in the literature; a characteristic feature is that every axis (with index x, y and z) occurs in the sequence of rotational axes. In German literature, these angles are sometimes called Cardan angles. Another possible definition of the orientation is the use of so-called Euler angles. In this definition, the first axis of rotation is, for example, the $\vec{e}_{ix}$-axis, the second is the $\vec{e}'_{iz}$-axis and the third, again about an x-axis, i.e. the $\vec{e}''_{ix}$-axis. In some MBS software as well as in ISO 8855 2011 we find the name Euler associated with the definition of Tait–Bryan angles. Consequently, you should read the exact definition of the sequence of rotations carefully and you should not simply assume that a particular convention applies.

When the vehicle is driving in a straight line, the $\vec{e}_{vx}$ and $\vec{e}_{ix}$ directions coincide. The first part of this course is limited to the straight-line motion of a vehicle (longitudinal dynamics) and considers resistances, driving performance and braking and acceleration processes. In this aspect of longitudinal dynamics, rotation of the vehicle always occurs about the $\vec{e}_{iy}$-axis. As mentioned above, this rotational motion about the $\vec{e}_{iy}$-axis is called pitch. Hence pitch and straight-line, forward motion are connected: as the centre of mass, S_{cm}, is above the road, every acceleration or braking manoeuvre causes inertia forces to act on S_{cm}, which yields a moment and therefore a pitch motion.

The second class of movements is caused by uneven roads. It is grouped together under the concept of vehicle vibrations. The movements are translations of the vehicle in the $\vec{e}_{iz}$ direction (bounce), rotation about $\vec{e}_{iy}$ direction (pitch) and the $\vec{e}_{ix}$ direction (roll).

In cornering, i.e. a non-constant yaw angle and in general the $\vec{e}_{ix}$ direction do not coincide with the $\vec{e}_{vx}$ direction, the vehicle, in addition to rotating about the $\vec{e}_{iz}$-axis, rotates about the $\vec{e}_{vx}$-axis (roll) and for deceleration or acceleration it rotates about the $\vec{e}_{vy}$-axis (pitch). A lateral motion also occurs. Cornering is investigated in the third part of this book, the lateral dynamics or cornering part.

These short considerations show that nearly always more than one degree of freedom is involved in the motion of the vehicle.

1.3 Questions and Exercises

Remembering

1. What kinds of models often describe the dynamics of vehicles?
2. How many degrees of freedom does the body of a vehicle have?
3. What are the names of the six degrees of freedom of the body associated with movements?
4. The dynamics of motor vehicles is usually divided into three main forms of movement. What are they?
5. What form of movement plays an important role in longitudinal dynamics?
6. What form of movement plays an important role in vertical dynamics?
7. What form of movement plays an important role in lateral dynamics?

Understanding

1. Which degrees of freedom of a vehicle are involved when passing a speed bump (same height for left and right wheels)?
2. Which degrees of freedom of a vehicle are involved when passing a pothole (at one side of the vehicle only)?

Applying

1. Which effects are the same when comparing a handcart with nearly stiff wheels which are fixed to the body without suspension and a vehicle with a centre of mass at the height of the road during acceleration or braking? Consider inertia forces and resulting moments.
2. Which effects are the same when comparing a handcart with nearly stiff wheels which are fixed to the body without suspension and a vehicle with a centre of mass at the height of the road during cornering? Consider centrifugal forces.