Chapter 1
Introduction

Vehicle dynamics is a fascinating subject, but it can also be very frustrating without the tools to truly understand it. We can try to rely on experience, but an objective knowledge needs a scientific approach. Something grounded on significant mathematical models, that is models complex enough to catch the essence of the phenomena under investigation, yet simple enough to be understood by a (well trained) human being. This is the essence of science, and vehicle dynamics is no exception.

The really important point is the mental attitude we should have in approaching a problem. We must be skeptical. We must be critical. We must be creative. Even if something is commonly accepted as obviously true, or if it looks very reasonable, it may be wrong, either totally or partially wrong. There might be room for some sort of improvement, for a fresh point of view, for something valuable.

Vehicle dynamics can be set as a truly scientific subject, it actually needs to be set as such to achieve a deep comprehension of what is going on when, e.g., a race car negotiates a bend.

When approached with open mind, several classical concepts of vehicle dynamics, like, e.g., the roll axis, the understeer gradient, even the wheelbase, turn out to be very weak concepts indeed. Concepts often misunderstood, and hence misused. Concepts that need to be revisited and redefined, and reformulated to achieve an objective knowledge of vehicle dynamics. Therefore, even experienced readers will probably be surprised by how some topics are addressed and discussed here.

To formulate vehicle dynamics on sound concepts we must rely on clear definitions and model formulations, and then on a rigorous mathematical analysis. We must, indeed, "formulate" the problem at hand by means of mathematical formulas [5]. There is no way out. Nothing is more practical than a good theory. However, although we will not refrain from using formulas, at the same time we will keep the analysis as simple as possible, trying to explain what each formula tells us.

To help the reader, the Index of almost all mathematical symbols is provided at the end of this book. The Index shows in which context each symbol is introduced and defined.

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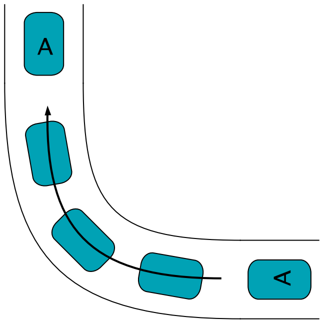

Fig. 1.1 Vehicle expected behavior when negotiating a curve

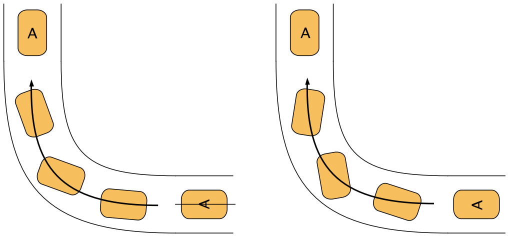

Fig. 1.2 Acceptable behaviors for a road vehicle

1.1 Vehicle Definition

Before embarking into the development of mathematical models, it is perhaps advisable to discuss a little what ultimately is (or should be) a *driveable road vehicle*. Since a road is essentially a long, fairly narrow strip, a vehicle must be an object with a clear *heading direction*.[1] For instance, a shopping cart is not a vehicle since it can go in any direction. Another common feature of road vehicles is that the driver is carried on board, thus undergoing the same dynamics (which, again, is not the case of a shopping cart).

Moreover, roads have curves. Therefore, a vehicle must have the capability to be driven in a fairly precise way. This basically amounts to controlling simultaneously the *yaw rate* and the magnitude and direction of the *vehicle speed*. To fulfill this task a car driver can act (at least) on the brake and accelerator pedals and on the steering wheel. And here it is where vehicle dynamics comes into play, since the outcome of the driver actions strongly depends on the vehicle dynamic features and state.

An example of proper turning of a road vehicle is something like in Fig. 1.1. Small deviations from this target behavior, like those shown in Fig. 1.2, may be tolerated. On the other hand, Fig. 1.3 shows two unacceptable ways to negotiate a bend.

All road vehicles have wheels, in almost all cases equipped with pneumatic tires. Indeed, also wheels have a clear heading direction. This is why the main way to steer a vehicle is by turning some (or all) of its wheels.[2]

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[1] Usually, children show to have well understood this concept when they move by hand a small toy car.

[2] Roughly speaking, wheels location does not matter to the driver. But it matters to engineers.

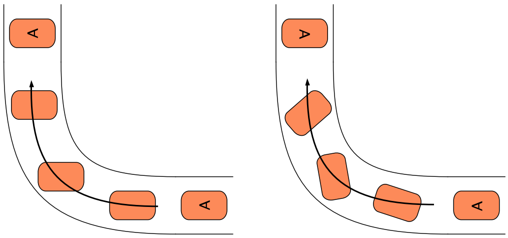

Fig. 1.3 Unacceptable behaviors for a road vehicle

To have good directional capability, the wheels in a vehicle are arranged such that their heading directions almost "agree", that is they do not conflict too much with each other. However, tires do work pretty well under small slip angles and, as will be shown, some amount of "disagreement" is not only tolerated, but may even be beneficial.

Wheel hubs are connected to the chassis (vehicle body) by means of suspensions. The number of possible different suspensions is virtually endless. However, suspension systems can be broadly classified into two main subgroups: dependent and independent [7, 9]. In a dependent suspension the two wheels of the same axle are rigidly connected together. In an independent suspension they are not, and each wheel is connected to the chassis by a linkage with "mainly" one degree of freedom. Indeed, the linkage has some compliance which, if properly tuned, can enhance the vehicle behavior.

1.2 Vehicle Basic Scheme

A mathematical model of a vehicle [6] should be *simple*, yet *significant* [1, 2]. Of course, there is not a unique solution. Perhaps, the main point is to state clearly the assumptions behind each simplification, thus making clear under which conditions the model can reliably predict the behavior of a real vehicle.

There are assumptions concerning the *operating conditions* and assumptions regarding the *physical model* of the vehicle.

Concerning the *operating conditions*, several options can be envisaged:

Performance: the vehicle goes straight on a flat road, possibly braking or accelerating (nonconstant forward speed);

Handling: the vehicle makes turns on a flat road, usually with an almost constant forward speed;

Ride: the vehicle goes straight on a bumpy road, with constant forward speed.

Obviously, real conditions are a mixture of all of them.

A significant, yet simple, *physical model* of a car may have the following features:

1. the vehicle body is a single rigid body;
2. each wheel hub is connected to the vehicle body by a one-degree-of-freedom linkage (independent suspension);
3. the steering angle of each (front) wheel is mainly determined by the angular position δ_v of the steering wheel, as controlled by the driver;
4. the mass of the wheels (unsprung mass) is very small if compared to the mass of the vehicle body (sprung mass);
5. the wheels have pneumatic tires;
6. there are springs and dampers (and, maybe, inerters) between the vehicle body and the suspensions, and, likely, between the two suspensions of the same axle (anti-roll bar). Front to rear interconnected suspensions are possible, but very unusual;
7. there may be aerodynamic devices, like wings, that may significantly affect the downforce.

The first two assumptions ultimately disregard the elastic compliances of the chassis and of the suspension linkages, respectively, while the third assumption leaves room for vehicle models with compliant steering systems.

A vehicle basic scheme is shown in Fig. 1.4, which also serves the purpose of defining some fundamental geometrical parameters:

1. the vehicle longitudinal axis x, and hence the vehicle heading direction $\mathbf{i}$;
2. the height h from the road plane of the center of gravity G of the whole vehicle;
3. the longitudinal distances a_1 and a_2 of G from the front and rear axles, respectively;
4. the lateral position b of G from the longitudinal axis x;
5. the wheelbase $l = a_1 + a_2$;
6. the front and rear tracks t_1 and t_2;
7. the geometry of the linkages of the front and rear suspensions;
8. the position of the steering axis for each wheel.

All these distances are positive, except possibly b, which is usually very small and hence typically set equal to zero, like in Fig. 1.4.

It must be remarked that whenever, during the vehicle motion, there are suspension deflections, several of these geometrical parameters may undergo small changes. Therefore, it is common practice to take their reference value under the so called *static conditions*, which means with the vehicle moving straight on a flat road at constant speed, or, equivalently if there are no wings, when the vehicle is motionless on a horizontal plane.

Accordingly, the study of the performance and handling of vehicles is greatly simplified under the hypothesis of small suspension deflections, much like assuming very stiff springs (which is often the case for race cars).[3] Yet, suspensions cannot

[3] However, handling with roll will be covered in Chap. 9, although at the expense of quite a bit of additional work.

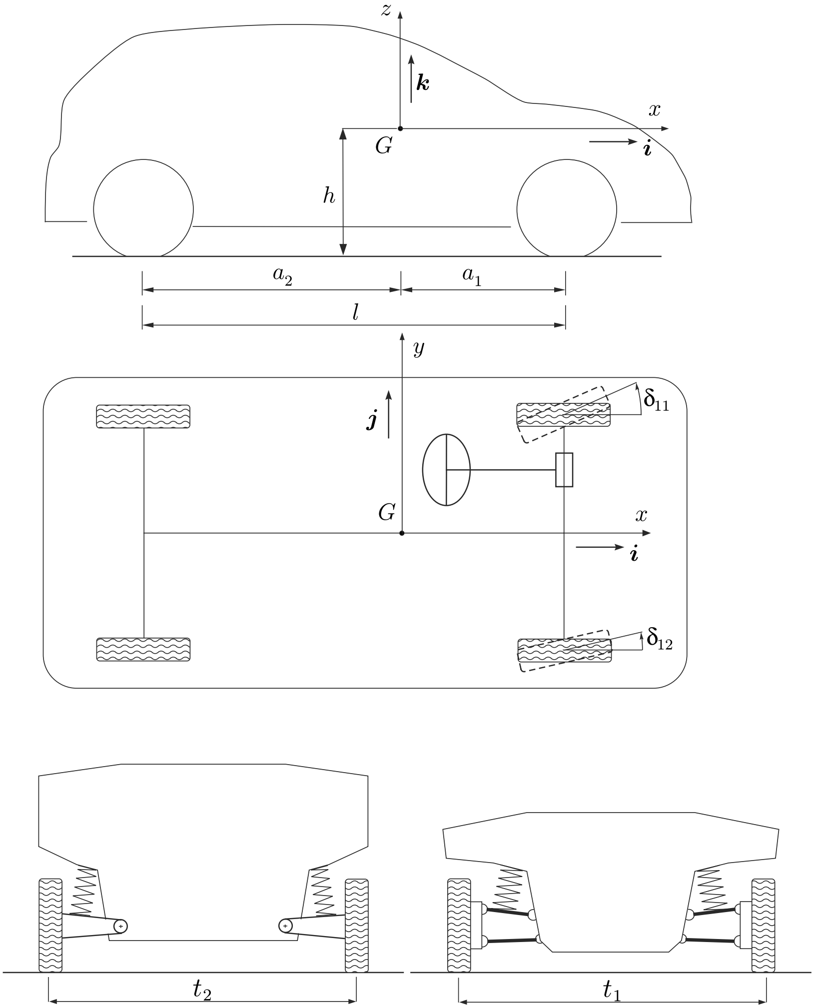

Fig. 1.4 Vehicle basic scheme and body-fixed reference system

be completely disregarded, at least not in vehicles with four or more wheels. This aspect will be thoroughly discussed.

The vehicle shown in Fig. 1.4 has a swing arm rear suspension and a double wishbone front suspension. Perhaps, about the worst and one of the best kind of independent suspensions [3, 4]. They were selected to help explaining some concepts, and should not be considered as an example of a good vehicle design. An example of a double wishbone front suspension is shown in Fig. 1.5.

As shown in Fig. 3.2, it is useful to define the *body-fixed reference system* $S = (x, y, z; G)$, with unit vectors $(\mathbf{i}, \mathbf{j}, \mathbf{k})$. It has origin in the center of mass G and axes

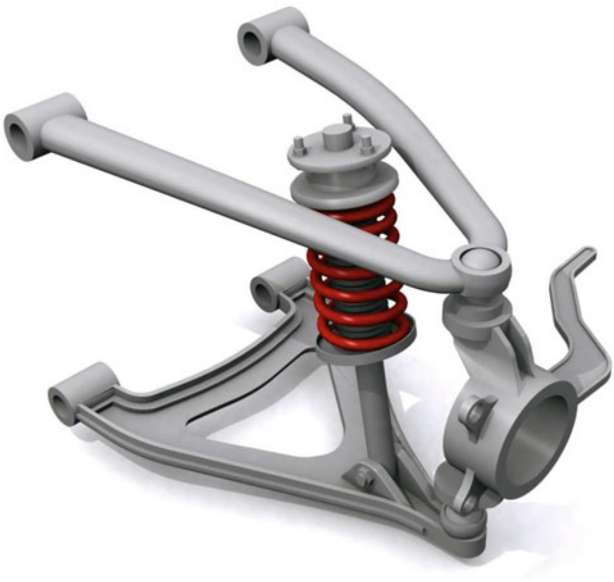

Fig. 1.5 Example of a double wishbone front suspension [8]

fixed relative to the vehicle. The horizontal x-axis marks the forward direction, while the y-axis indicates the lateral direction. The z-axis is vertical, that is perpendicular to the road, with positive direction upward.

References

1. Arnold M, Burgermeister B, Fuehrer C, Hippmann G, Rill G (2011) Numerical methods in vehicle system dynamics: state of the art and current developments. Veh Syst Dyn 49(7):1159–1207
2. Cao D, Song X, Ahmadian M (2011) Editors' perspectives: road vehicle suspension design, dynamics, and control. Veh Syst Dyn 49(1–2):3–28
3. Genta G, Morello L (2009) The automotive chassis, vol 1. Springer, Berlin
4. Genta G, Morello L (2009) The automotive chassis, vol 2. Springer, Berlin
5. Guiggiani M, Mori LF (2008) Suggestions on how not to mishandle mathematical formulæ. TUGboat 29:255–263
6. Heißing B, Ersoy M (eds) (2011) Chassis handbook. Springer, Wiesbaden
7. Jazar RN (2014) Vehicle dynamics, 2nd edn. Springer, New York
8. Longhurst C (2013) https://www.carbibles.com/guide-to-car-suspension/
9. Schramm D, Hiller M, Bardini R (2014) Vehicle dynamics. Springer, Berlin