CHAPTER

Introduction

1

To undertake a numerical process without knowledge of the difference between good and bad numbers is folly.

Damian Harty, 2014

1.1 Overview

In 1969, man travelled to the moon and back, using mathematics invented by Kepler, Newton and Einstein to calculate trajectories hundreds of thousands of miles long and spacecraft with less on-board computing power than a mobile telephone.[1] With today's computing power and the mathematical frameworks handed down to us by Newton and Lagrange, it is scarcely credible that the motor car, itself over 100 years old, can exercise so many minds and still show scope for improvement. Yet we are still repeating errors in the dynamic design of our vehicles that were made in the 1960s. Every car will spin — rotate excessively about a vertical axis until it is no longer pointing where it is going — if driven through an emergency lane change at highway speed without skilled correction from the driver or from computer-controlled stability systems (or both).

Legislation now demands embedded electronic control of brake systems to retain control and stability of vehicles although the driver still retains executive control in terms of choosing speed and path. However, with the exception of braking performance, road vehicle manufacturers are not currently forced by legislation to achieve a measurable standard of vehicle handling and stability. International standards exist that outline procedures for proving ground tests with new vehicles but these are nothing more than recommendations. Vehicle manufacturers make use of many of the tests but in the main will develop and test vehicles using in-company experience and knowledge to define the test programme.

In the absence of legislated standards, vehicle manufacturers are driven by market forces. Journalists report favourably on vehicles they enjoy driving — whether or

[1]The Apollo Guidance Computer (AGC) had 2 kB of memory, 32 kB of non-rewritable flash drive and 1 MHz clock speed. A typical smart phone at the time of writing has 1000 kB of memory, 32 million kB of rewritable flash drive and a clock speed of 1000 MHz.

The Multibody Systems Approach to Vehicle Dynamics. http://dx.doi.org/10.1016/B978-0-08-099425-3.00001-7

not these are safe in the hands of the general public — and the legal profession seeks every opportunity to blur the distinction between bad driving and poor vehicle design. Matters are further complicated by market pressures driving vehicle designs to be too tall for their width — city cars and sport-utility vehicles have this disadvantage in common.

The growth in media attention and reporting to the public is undoubtedly significant. When the first edition was written, the most well-publicised example of this was the reported rollover of the Mercedes A Class (top left image in Figure 1.1) during testing by the Motoring Press. The test involves a slalom type manoeuvre and became popularly known as the 'Elk Test' or 'Moose Test'. With the arrival of YouTube in 2005, everyone is a journalist. A short search netted three more examples of well-performed tests illustrating other vehicles in disarray. No manufacturer wants videos like these going viral.

It seems to the authors that there are two camps for addressing the vehicle dynamics problem. In the first camp are the practical ride and handling experts. Skilled at the driving task and able to project themselves into the minds of a variety of different possible purchasers of the vehicle, they are able to quickly take an established vehicle design and adjust its character to make it acceptable for the market into which it will be launched. Rarely, though, are experts from this camp called upon to work in advance on the concept or detail of the vehicle design.

The second camp contains theoretical vehicle dynamics experts. They are skilled academics in the mould of Leonard Segel who in 1956 published his 'Theoretical prediction and experimental substantiation of the responses of the automobile to steering control' (Segel, 1956).

FIGURE 1.1

Two-wheel lift abounds. (Top left — Mercedes courtesy of Auto Motor und Sport). There are two very similar tests being used, one is the ISO3888 Lane Change and the other is an ADAC avoidance test.

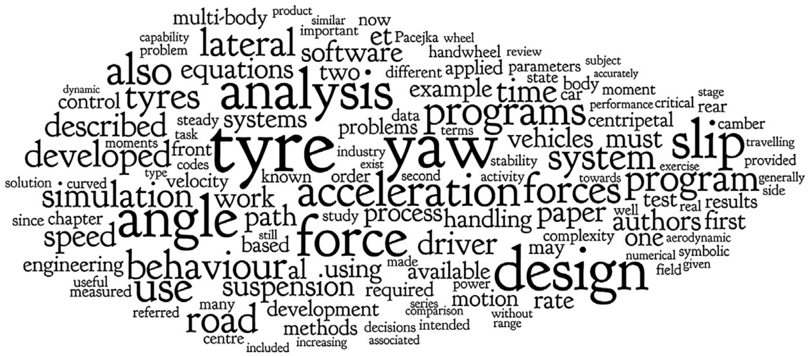

FIGURE 1.2

What vehicle dynamics looks like to outsiders.

Segel's work, and that of others from this era including the earlier work 'Road manners of the modern motor car' (Olley, 1945), laid the ground for all subsequent 'classical' vehicle dynamic analysis and forms a firm foundation upon which to build. It is rare for an expert from this camp to be part of the downstream vehicle development process.

These two camps, a little like England and the USA, are 'separated by a common language'.[2] They use similar terms very differently (Figure 1.2) and can often have contemptuous relationships in a given organisation.

The 'word cloud' diagram in Figure 1.2 was generated by taking the contents of this chapter and pasting them into www.wordle.net. After removing some trivial common words, this is what remains. The size of the word reflects how often it appears; it seems that conversations about vehicle dynamics are dominated by talk of tyres and yaw. The latter is a rotation of the vehicle about a vertical axis.

1.2 What is vehicle dynamics?

The field known as vehicle dynamics is concerned with two aspects of the behaviour of the machine. The first is isolation and the second is control. Figure 1.3 is the authors' subjective illustration of the intricacy and interconnection of the tasks to be approached; it is not claimed to be authoritative or complete but is rather intended as a thought-starter for the interested reader.

Isolation is about separating the driver from disturbances occurring as a result of the vehicle operation. This, too, breaks into two topics; disturbances the vehicle generates itself (engine vibration and noise, for example) and those imposed upon it by the outside world. The former category is captured by the umbrella term

[2]Often attributed to George Bernard Shaw, this quote cannot actually be found in his writings anywhere according to Wikipedia.

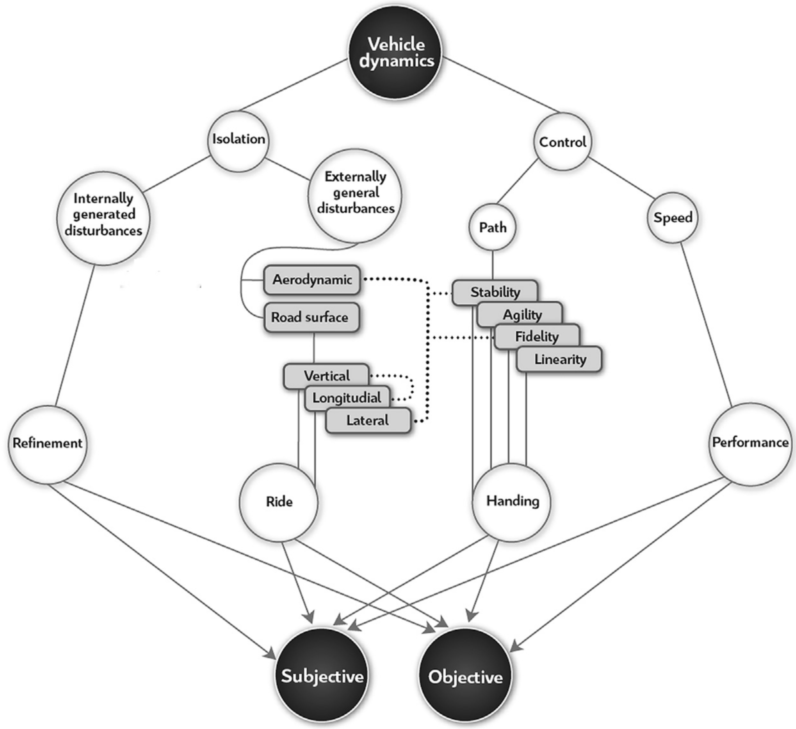

FIGURE 1.3

Vehicle dynamics interactions.

'refinement'. The disturbances in the latter category are primarily road undulations and aerodynamic interaction of the vehicle with its surroundings − crosswinds, wakes of structures and wakes of other vehicles. The behaviour of the vehicle in response to road undulations is referred to as 'ride' and could conceivably be grouped with refinement, though it rarely is in practice.

There is some substantial crossover in aerodynamic behaviour between isolation and control, since control implies the rejection of disturbances ('fidelity') and an absence of their amplification ('stability'). Similarly, one response to road disturbances is a change in the vertical load supported by the tyre; this has a strong influence on the lateral force the tyre is generating at any given instant in time and is thus crucial for both fidelity and stability. It can be seen with some little reflection that one of the difficulties of vehicle dynamics work is not the complexity of the individual effects being considered but rather the complexity of their interactions.

Control is concerned largely with the behaviour of the vehicle in response to driver demands. The driver continuously varies both path curvature and speed, subject to the limits of the vehicle capabilities, in order to follow an arbitrary course.

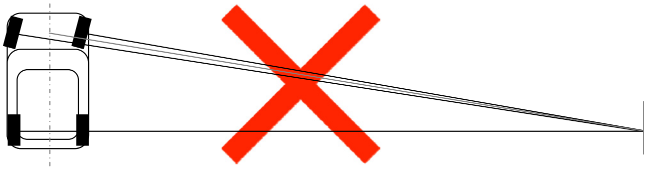

FIGURE 1.4

Geometric approximations of vehicle behaviour are incorrect.

Speed variation is governed by vehicle mass and tractive power availability at all but the lowest speed, and is easily understood. Within the performance task, issues such as unintended driveline oscillations and tractive force variation with driver demand may interact strongly with the path of the vehicle.

The adjustment of path curvature at a given speed is altogether more interesting. In a passenger car, the driver has a steering wheel, which for clarity will be referred to as a *handwheel*[3] throughout the book. The handwheel is a 'yaw rate' demand — a demand for rotational velocity of the vehicle when viewed from above. The combination of a yaw rate and a forward velocity vector that rotates with the vehicle gives rise to a curved path. There is a maximum path curvature available in normal driving, which is the turning circle, available only at the lowest speeds.

It is generically true that the vehicle does not behave in a 'geometric' manner and its radius of turn cannot usefully be predicted by considering the angle of the front wheels relative to the rear wheels, except below around 30 mph.

The geometric view (Figure 1.4) becomes increasingly inaccurate as speed increases and can lead to an over-estimate of vehicle responses by a factor of up to four at European highway speeds. The lower-than-geometric response of the car is a consequence of pneumatic tyres and modern vehicle engineering practice; it is not necessarily the 'unengineered' behaviour of all vehicle layouts.

In normal circumstances (that is to say in day-to-day road use) the driver moves the handwheel slowly and is well within the limits of the vehicle capability. The vehicle has no difficulty responding to the demanded yaw rate. If the driver increases yaw rate demand slightly then the vehicle will increase its yaw rate by a proportional amount (Figure 1.5). This property is referred to as 'linearity'; the vehicle is described as 'linear'. For the driver, the behaviour of the vehicle is quite instinctive. A discussion of the analysis and interpretation of vehicle non-geometric behaviour, linearity and departure from linearity is given in Chapter 7.

In the linear region, the behaviour of the vehicle can be represented as a connected series of 'steady state' events. Steady state is the condition in which, if the handwheel remains stationary then all the vehicle states — speed, yaw rate, path

[3]'Steering Wheel' could mean a roadwheel that is steered, or a wheel held by the driver. In generic discussions including vehicles other than four wheeled passenger cars (motorcycles, tilting tricycles, etc.) 'steering wheel' contains too much ambiguity; therefore 'handwheel' is preferred since it adds precision.

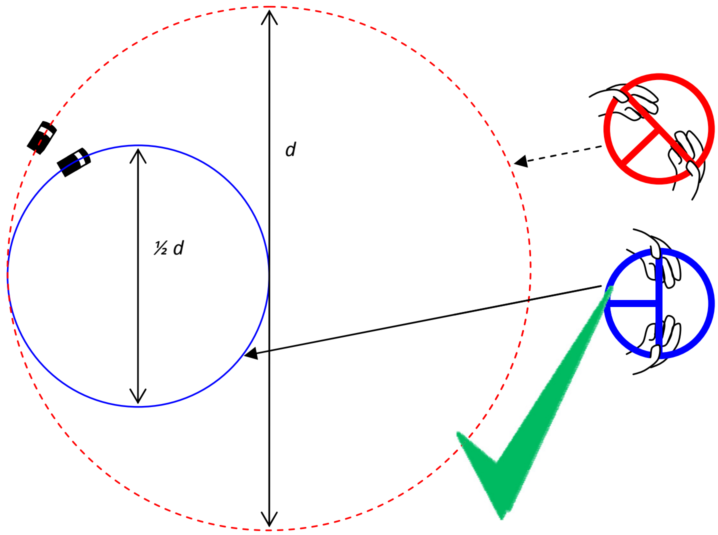

FIGURE 1.5

Linearity: More handwheel input results in proportionally more yaw rate.

curvature and so on — remain constant and is more fully defined in Chapter 7. The steady state condition is easy to represent using an equilibrium analogy, constructed with the help of so-called 'centrifugal force'. It should be noted that this fictitious force is invented solely for convenience of calculation of the analogous equilibrium state or the calculation of forces in an accelerating frame of reference. When a vehicle is travelling on a curved path it is not in equilibrium.

The curved path of the vehicle requires some lateral acceleration. Correctly, the lateral acceleration on a cornering vehicle is a centripetal acceleration — 'centre seeking'. Note that speed is not the same as velocity; travelling in a curved path with a constant speed implies a changing direction and therefore a changing velocity. Even the centripetal acceleration definition causes some problems since everyone

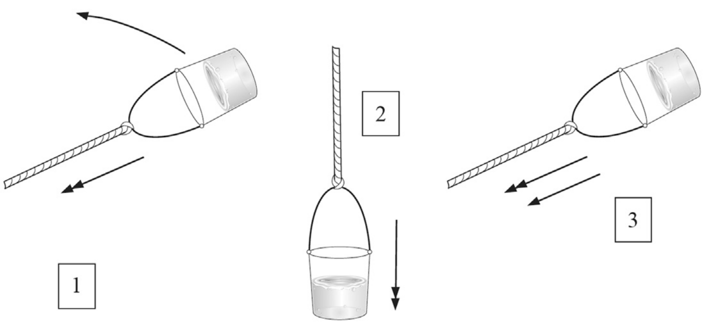

FIGURE 1.6

Thought experiment comparing centripetal acceleration with linear acceleration.

'knows' that they are flung to the outside of a car if unrestrained and so there is much lax talk of centrifugal forces — 'centre fleeing'. To clarify this issue, a brief thought experiment is required. Imagine a bucket of water on a rope being swung around by a subject (Figure 1.6). If the subject looks at the bucket then the water is apparently pressed into the bucket by the mythical 'centrifugal force' (presuming the bucket is being swung fast enough). If the swinging is halted and the bucket simply suspended by the rope then the water is held in the bucket by the downward gravitational field of the earth — the weight of the water pulls it into the bucket. Imagine now a different scenario in which the bucket (on a frictionless plane) is pulled horizontally towards the observer at a constant acceleration in a linear fashion. It's best not to complicate the experiment by worrying about what will happen when the bucket reaches the subject. It is this third scenario and not the second that is useful in constructing the cornering case. If both the first and third cases are imagined in a zero gravity environment, they still work — the water will stay in the bucket. Note that for the third scenario — what we might call the 'inertial' case as against the gravitational case in the second scenario — the acceleration is towards the open end of the bucket. This is also true for the first scenario, in which the bucket is swung; the acceleration is towards the open end of the bucket and is towards the subject — i.e. it is centripetal. That the water stays in the bucket is simply a consequence of the way the bucket applies the centripetal force to the water. Thus the tyres on a car exert a force towards the centre of a turn and the body mass is accelerated by those forces centripetally — in a curved path.

An accelerometer in the car is effectively a load cell that would be between the bucket and the water in the scenarios here and so it measures the centripetal force applied between the calibrated mass within the accelerometer (the water) and its support in the casing (the bucket). The so-called centrifugal force is one half of an action—reaction pair within the system but a free-body diagram of the bucket and rope in all three cases shows tension in the rope as an externally applied force when considering the rope as a separate free body. Only in case 2 is the bucket actually in equilibrium, with the addition of the gravitational force on the bucket and water. Therefore an accelerometer (or an observer) in the vehicle apparently senses a centrifugal force while theoretical vehicle dynamicists talk always of centripetal acceleration. Changing the sign on the inertial force, so that it is now a d'Alembert force, appears to solve the apparent confusion. This can be misleading as we now have the impression that the analysis of the cornering vehicle is a static equilibrium problem. The water is not in equilibrium when travelling in a curved path, and neither is a car.

Centripetal forces accelerate the vehicle towards the centre of the turn. This acceleration, perpendicular to the forward velocity vector, is often referred to as 'lateral' acceleration, since the vehicle broadly points in the direction of the forward velocity vector (see Chapter 7 for a more precise description of the body attitude). It can be seen that the relationship between centripetal acceleration, A^p, yaw rate, ω, forward velocity, V and radius of turn, R is given by:

$$A^p = V^2/R = \omega V = \omega^2 R \tag{1.1}$$

The absolute limit for lateral acceleration, and hence yaw rate, is set by the friction available between the tyres and the road surface. Competition tyres ('racing slicks') have a coefficient of friction substantially in excess of unity[4] and, together with large aerodynamic downforces, allow a lateral acceleration in the region of 30 m/s^2, with yaw rates correspondingly over 40 deg/s for a speed of 40 m/s (90 mph). For more typical road vehicles, limit lateral accelerations rarely exceed 9 m/s^2, with yaw rates correspondingly down at around 12 deg/s at the same speed. However, for the tyre behaviour to remain substantially linear for a road car, the lateral accelerations must be generally less than about 3 m/s^2, so yaw rates are down to a mere 4 deg/s at the same speed.

While apparently a small fraction of the capability of the vehicle, there is much evidence to suggest that the driving population as a whole rarely exceed the linearity limits of the vehicle at speed and only the most confident exceed them at lower speeds (Lechmer and Perrin, 1993). The 100 Car Naturalistic Driving Study categorises any event greater than 4 m/s^2 as a 'near accident' or 'dangerous occurrence' (Dingus et al., 2004).

When racing or during emergency manoeuvres on the road − typically attempting to avoid an accident − the vehicle becomes strongly 'non-linear'. The handwheel is moved rapidly and the vehicle generally has difficulty in responding accurately to the handwheel. This is the arena called 'Transient Handling' and is correctly the object of many studies during the product design process. In contrast to the steady state condition, all the vehicle states fluctuate rapidly and the expressions above are modified. Steady state and transient behaviour are connected. While good steady state behaviour is connected with good transient behaviour, it is not in itself sufficient (Sharp, 2000).

Transient handling studies concentrate on capturing, analysing and understanding the yaw moments applied to the vehicle and its response to them. Those moments are dominated by the lateral and longitudinal forces from the tyres. For road cars, additional aerodynamic contributions are a small modifier but for racing, the aerodynamic behaviour rises in importance.

The generation of tyre forces is frequently the biggest source of confusion in vehicle dynamics, since both lateral and longitudinal mechanisms are neither obvious nor intuitive. Tyres are dealt with in some depth by Pacejka (2012) in a companion volume in this series and also have some further coverage in Chapter 5.

The tyres generate lateral forces by two mechanisms, 'camber' and 'slip angle'. Camber is the angle at which the tyre is presented to the road when viewed from the front. There exists some confusion when referring to and measuring camber angle; for clarity within this text camber angle is measured with respect to the road[5] unless

[4]Some people are troubled by this idea but the authors have never been able to understand why. In any case, the performance of top fuel dragsters should leave no doubt that friction coefficients handsomely above unity exist.

[5]This is referred to as 'inclination angle' in some contexts.

explicitly defined as being relative to the vehicle body. It is the angle with respect to the road that generates a side force. Thus a motorcycle runs a large camber angle when cornering but runs no camber angle with respect to the vehicle body.

Slip angle is the angle at which the moving tyre is presented to the road when viewed in plan. It is important to note that slip angle only exists when the vehicle is in motion. At a standstill (and at speeds under about 10 mph) the lateral stiffness of the tyres generate the forces that constrain the vehicle to its intended path. As speed rises above walking pace, the tyres have a falling static lateral stiffness until above about 5 m/s (about 10 mph) they have effectively none; an applied lateral force, such as a wind load, will move the vehicle sideways from its intended path. It is important to note that the presence of a slip angle does not necessarily imply sliding behaviour at the contact patch.

Slip angle forces are typically more than 20 times camber forces for a particular angle, and are thus the more important aspect for vehicle dynamics. The lateral forces induced by the angles are strongly modified by the vertical loads on the tyres at each moment in time.

The tyres generate longitudinal forces by spinning at a speed different to their 'free-rolling' speed. The free-rolling speed is the speed at which the wheel and tyre would spin if no brake or drive forces are applied to them. The difference in speed is described as 'slip ratio', which is unfortunate since it is confusingly similar to slip angle. It is expressed as a percentage, so for example a tyre turning with a 5% slip ratio will perform 105 revolutions to travel the same distance as a free-rolling tyre performing 100 revolutions. In doing so, it will impart a tractive force to the vehicle. A −5% slip ratio would imply 95 revolutions of the same wheel and the presence of a braking force.

Managing lateral tyre forces by controlling slip and camber angles is the work of the suspension linkage. For the front wheels, the driver has the ability to vary the slip angle using the handwheel. Managing the vertical loads on the tyres is the function of the suspension 'calibration' (springs, dampers and any active devices, if present). Chapter 4 deals with suspension analysis in some detail. Management of longitudinal forces is the role of the vehicle driveline and braking system, including anti-lock braking system or brake intervention systems, dealt with in Chapter 8.

A vehicle travelling in a straight line has a yaw velocity of zero and a centripetal acceleration of zero. When travelling in a steady curve, the centripetal acceleration is not zero and the yaw rate is not zero but both are constant and are related as described in Eqn (1.1). In performing the transition from straight running to a curved path there must be a period of yaw acceleration in order to acquire the yaw velocity that matches the centripetal acceleration. The yaw acceleration is induced and controlled by yaw moments acting on the vehicle yaw inertia.

Transient handling therefore implies the variation of yaw moments applied to the vehicle. Those moments are applied by aerodynamic behaviour and the force-generating qualities of the tyres at a distance from the vehicle's centre of mass. No other mechanisms exist for generating a meaningful yaw moment on the vehicle; while gyroscopic torques associated with camber changes exist, they are small. For road vehicles, the aerodynamic modifications are generally small. Multibody system methods allow the convenient exploration of aspects of the vehicle design that influence those qualities of the tyres. Chapter 6 addresses different methods of modelling those aspects of the vehicle and their relative merits.

The modelling of the tyre forces and moments at the tyre to road contact patch is one of the most complex issues in vehicle handling simulation. The models used are typically not causal[6] but are rather empirical formulations used to represent the tyre force and moment curves typically found through laboratory or road based rig testing of a tyre.

Like all models, tyre models have a spectrum of complexity ranging from simple vertical spring rates with hysteretic damping through to fully causal. Chapter 5 explores this spectrum in some depth. Examples of tyre models used for vehicle handling discussed in this book include:

1. A sophisticated empirical point-follower tyre model known as the 'Magic Formula'. This tyre model has been developed by Pacejka and his associates (Bakker et al., 1986, 1989; Pacejka and Bakker, 1993; Pacejka, 2012) and is known to give usefully accurate representation of measured tyre characteristics. The model uses modified trigonometric functions to represent the shape of curves that plot tyre forces and moments as functions of longitudinal slip or slip angle. For 25 years the work of Pacejka has been well known throughout the vehicle dynamics community. The result of this is a tyre model that is now widely used both by industry and academic institutions and is undergoing continual improvement and development. The complexity of the model does however mean that well over 50 parameters are needed to define a tyre model and that software must be obtained or developed to derive the parameters from measured test data. The latest versions of the model (6.1 at the time of writing) include the effects of inflation pressure and can accommodate motorcycle and passenger car tyres within the same model.
2. An alternative modelling approach is to use a straightforward interpolation model. This was the original tyre modelling method used in MSC ADAMS (Ryan, 1990). This methodology is still used by some companies but has, to a large extent, been superseded by more recent parameter based models. The method is included here as a useful benchmark for the comparison of other tyre models in Chapter 5.
3. Another point-follower tyre model is provided for readers as a source listing in Appendix B. This model (Blundell, 2003) has been developed by Harty and has

[6]A Causal model is one in which the causes for every effect produced are explicitly described. An example might be a finite element model of a spring, which infers the behaviour of the whole spring from constituent stress/strain relationships. An empirical model is one assembled entirely from observations but making no attempt to quantify or describe the mechanisms causing the effect. An example might be the linear elastic equation of a spring, which requires and produces no description of the stress or strain state of the metal.

the advantage of requiring only a limited number of input parameters compared to the Pacejka model. The implementation is more complete, however, than the interpolation model and includes representation of the following:

a. Comprehensive slip
b. Load dependency
c. Camber thrust
d. Post limit

It has been found that the Harty model is robust when modelling limit behaviour including for example problems involving low grip or prolonged wheelspin. The same model is suitable for representing motorcycle and passenger car tyre behaviour when different parameters are employed.

4. An elaborate 'semi-causal' model of the tyre structure known as FTire (Gipser, 1999), sold commercially including carcase enveloping and contact patch velocity details. Based on an elegant formulation, conceptually a blend of finite element-style simultaneous solutions of small segments with a modal-component style aggregate behaviour representation, it boasts some impressive abilities to resolve pressure and velocity distributions in the contact patch. It is gaining ground in durability prediction in particular.
5. A further model, which is less elaborate than (4) structurally but incorporates thermal aspects in order to be able to migrate from cold to hot and from fresh to worn during the course of a simulation. Of particular interest in motorsport where the thermal modification of tyres is most marked, the so-called Thermal And MEchanical (TAME Tire) representation (Hague, 2010), complements the FTire approach and is more appropriate for certain applications

These five approaches to tyre modelling represent a comprehensive overview of the breadth of modelling practice now in use and are a substantial expansion over what was common when the first edition was written.

In order to progress from travelling in a straight line to travelling in a curved path, the following sequence of events is suggested:

1. The driver turns the handwheel, applying a slip angle at the front wheels.
2. After a delay associated with the front tyre relaxation lengths (see Chapter 5), side force is applied at the front of the vehicle. Lateral and yaw accelerations exist.
3. The body yaws (rotates in plan), applying a slip angle at the rear wheels.
4. After a delay associated with the rear tyre relaxation lengths, side force is applied at the rear of the vehicle. Lateral acceleration is increased; yaw acceleration is reduced to zero.

In the real world, the driver intervenes and the events run into one another rather than being discrete as suggested here, but it is a useful sequence for discussion purposes. A similar sequence of events describes the return to straight-line travel. Any yaw rate adjustments made by the driver follow similar sequences, too.

During the period of yaw acceleration (stages 2 and 3 above) there exists the need for an excess of lateral forces from the front tyres when compared to the rear in order to deliver the required yaw moment. At the end of this period, that excess must disappear. Side force requirements for the rear tyre are thus increasing while those for the front tyres are steady or decreasing. To understand the significance of this fact, some further understanding of tyre behaviour is necessary.

To a first approximation, camber forces may be neglected from tyre behaviour for vehicles that do not roll (lean) freely. Slip angle is the dominant side force generation mechanism. It is important to note that a tyre will adjust its slip angle to support the required side force, and not the other way around; this is a frequent source of difficulty in comprehending vehicle dynamic behaviour. All tyres display a slip angle at which the maximum side force is generated, sometimes referred to as the 'critical slip angle'. If a force is required which is greater than that which can be generated at the critical slip angle, the tyre will run up to and then beyond the critical slip angle. Beyond the critical slip angle the side force falls off with slip angle, and so an increasing amount of surplus lateral force is available to accelerate the growth of slip angle once the critical slip angle is passed.

Returning to the vehicle, the side force requirement for the rear tyres is increasing while that for the front tyres is steady or decreasing. The rear tyres will be experiencing a growing slip angle, while the fronts experience a steady or reducing one. If at this time the rear tyres exceed their critical slip angle, their ability to remove yaw moment is lost. The only possible way for yaw moment to be removed is by a reduction in the front tyre forces. If the yaw moment persists then yaw acceleration persists. With increasing yaw velocity, the slip angle at the front axle is reduced while that at the rear axle is increased further, further removing the rear tyres' ability to remove yaw moment from the vehicle. If the front tyres are past their critical slip angle, too, the normal stabilisation mechanism is reversed. The result is an accelerating spin that departs rapidly from the driver's control. The modelling and interpretation of such events is dealt with in Chapter 7.

The behaviour of the driver is important to the system performance as a whole. The driver is called on to act as a yaw rate manager, acting on the vehicle controls as part of a closed-loop feedback system to impart the yaw moments required to control the yaw rate of the vehicle. At critical times, the workload of the driver may exceed his or her capability, resulting in a loss of control.

The goal of vehicle dynamics work is to maintain the vehicle behaviour within the bounds that can be comprehended by and controlled by the driver. The increasing use of electronic systems in vehicles drives the application of standards for the safe engineering of such critical standards, the most common of which is the ISO26262 standard for automobiles. So-called 'controllability' is a key factor in this and multibody simulations have an important role in assessing the controllability of many situations, as discussed later in Chapter 8.

1.3 Why analyse?

In any real product-engineering programme, particularly in the ground vehicle industry, there are always time constraints. The need to introduce a new product to retain market share or to preserve competitive advantage drives increasingly tight timetabling for product-engineering tasks. In the western world, and to a growing extent in the developing world, tastes are becoming ever more refined such that the demand for both quality of design and quality of construction is increasing all the while. Unlike a few decades ago, there are few genuinely bad products available.

It seems, therefore, that demands for better products are at odds with demands for compressed engineering timetables. This is true; the resolution of this conflict lies in improving the efficiency of the engineering process. It is here that predictive methods hold out some promise.

Predictive methods notionally allow several good things:

- Improved comprehension and ranking of design variables
- Rapid experimentation with design configurations
- Genuine optimisation of numerical response variables

Therefore the use of predictive methods is crucial for staying ‘ahead of the game’ in vehicle engineering.

1.4 Classical methods

These methods are taught formally in universities as part of the syllabus. While they can be daunting at first sight, they are elegant and can prove tremendously illuminating in forming a holistic framework for what can easily be a bewildering arena. A quick tour through a classically formulated vehicle model is given in Chapter 7 and an implementation in MS-Excel is available to download with the book.

The best practitioners of the art recommend the use of a body-centred state-space formulation. While full of simplifications, useful insights can be gained by studying a two degree-of-freedom model for typical passenger cars. With a reasonable increase in sophistication but well worth the effort is the elaboration to three degrees of freedom (four states) to include the influence of suspension roll.

Such classical models help the analyst discern ‘the wood for the trees’ – they easily bring forth, for example, the influence of suspension steer derivatives on straight-line stability. In this they contrast strongly with ‘literal’ linkage models, in which all the problems of real vehicles (the lack of isolation of single effects) obscures their ranking and comprehension.

Although the task of deriving the equations of motion and arranging the terms for subsequent solution is laborious and may be error-prone, the proponents of the method point quite correctly to the increased comprehension of the problem to which it leads.

1.5 Analytical process

It is clear that the tasks undertaken have expanded to fit the time available. Despite remorselessly increasing computing power, analysis tasks are still taking as long to complete as they always have done. The increased computing power available is an irresistible temptation to add complexity to predictive models (Harty, 1999).

Complex models require more data to define them. This data takes time to acquire. More importantly, it must exist. Early in the design cycle, it is easy to fall into the 'paralysis of analysis'; nothing can be analysed accurately until it is defined to a level of accuracy matching the complexity of the modelling technique. More than the model itself, the process within which it fits must be suited to the tasks at hand. *The model is not the product!*

There is nothing new in the authors' observations; Sharp (1991) comments

> *Models do not possess intrinsic value. They are for solving problems. They should be thought of in relation to the problem or range of problems which they are intended to solve. The ideal model is that with minimum complexity which is capable of solving the problems of concern with an acceptable risk of the solution being "wrong". This acceptable risk is not quantifiable and it must remain a matter of judgement. However, it is clear that diminishing returns are obtained for model elaboration.*

Any method of analysis must be part of a structured process if it is to produce useful results in a timely manner. Interesting results that are too late to influence product design are of little use in modern concurrent[7] engineering practice. Rapid results that are so flawed as to produce poor engineering decisions are also of little use. The use of predictive methods within vehicle design for addressing dynamic issues with the vehicle should follow a pattern not dissimilar to that in Figure 1.7, whatever the problem or the vehicle.

1.5.1 Aspiration

The method properly starts with the recognition of the end goals. In some organisations, confusion surrounds this part of the process, with obfuscation between targets, objectives and goals; the terms are used differently between organisations and frequently with some differences between individuals in the same organisation. Cutting through this confusion requires time and energy but is vital.

1.5.2 Definition

After definition, a clear description of 'success' and 'failure' must exist; without it the rest of the activities are, at best, wasteful dissipation. Aspirations are frequently set in terms of subjective comparisons – 'Ride Comfort better than best in class'.

[7]Concurrent = Taking place at the same time. 'Concurrent Engineering' was a fashionable phrase in the recent past and refers to the practice of considering functional, cost and manufacturing issues together rather than the historically derived 'sequential' approach. It was also referred to as 'Simultaneous Engineering' for a while, though the segmented connotations of simultaneous were considered unhelpful and so the 'concurrent' epithet was adopted.

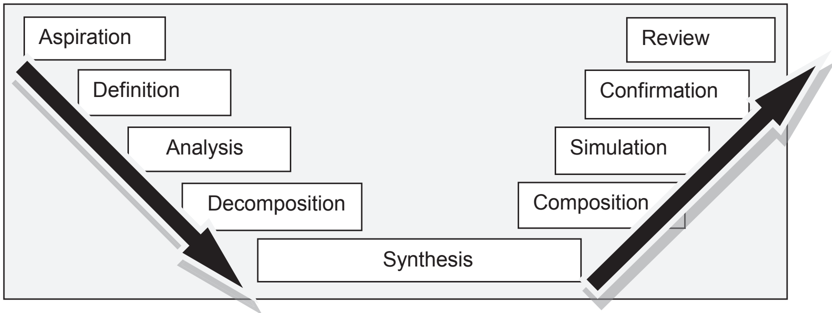

FIGURE 1.7

'V' Process for product design.

To usefully feed these into an analytical process, they must be capable of being quantified – i.e. of having numbers associated with them. Without numbers, it is impossible to address the task using analytical methods and the analytical process should be halted. This is not to say that product development cannot continue but that *to persist with a numerical process in the absence of a knowledge of the difference between good and bad numbers is folly.* Analysts and Development staff must be involved closely with each other and agree on the type of numerical data that defines success, how it is calculated predictively and how it is measured on a real vehicle. Commonly, some form of 'benchmarking' study – a measurement exercise to quantify the current best performers – is associated with this stage. The activity to find the benchmark is a useful shakedown for the proposed measurement processes and is generally a fruitful education for those involved.

1.5.3 Analysis

When success and failure have been defined for the system as a whole, the individual parts of the system must be considered. There is generally more than one way to reach a system solution by combining individual subsystems or elements. During this stage of the process, some decisions must be taken about what combination is preferred. It may be, for example, that in seeking a certain level of vehicle performance there is a choice between increasing power output and reducing weight in order to achieve a given power-to-weight ratio. That choice will be influenced by such simple things as cost (saving weight may be more expensive than simply selecting a larger engine from the corporate library) or by more abstruse notions (the need to be seen to be 'environmentally friendly', perhaps). The task of analysis is to illuminate that choice. The analysis carried out must be sufficiently accurate but not excessively so. 'Simple models smartly used' is the order of the day for analysis work. The analysis may consider many possible combinations in order to recommend a favoured combination. This activity is sometimes referred to by the authors as 'mapping the design space' – producing guidance for those who wish to make design decisions based on wider considerations and who wish to comprehend the consequences of their decisions. *The most cost-effective activity at this stage is accurately recalling and comprehending what has gone before*. Since the first edition of the book, ‘design of experiments’ and ‘signal to noise’ software has matured tremendously and with tools such as Minitab, Mode Frontier, Heeds, Altair Hyperstudy or MSC Insight, this mapping process can be undertaken more diligently than ever before. Chapter 7 discusses these new possibilities in more detail.

1.5.4 Decomposition

Once the analytical stage is complete, it is time for design decisions to be made. The whole entity must be decomposed into its constituent parts, each of which has design goals associated with it – cost, performance, weight, etc. It is at this time the first real design decisions are made that shape the product – section properties, geometries, manufacturing process and so on. Those decisions are to be made in the light of the preceding analysis. Many organisations still begin this part of the process too early and as a consequence paint themselves into a corner.

1.5.5 Synthesis

Once the design is decomposed into manageable portions, the task of synthesising (creating) the design begins. During this phase, analytical tools are used to support individual activities and verify the conformance of the proposed design with the intended design goals. An example of this might be the use of kinematic simulation to verify that the suspension geometry characteristics are those required. Discerning the requirement itself is the function of the earlier decomposition phase.

1.5.6 Composition

The reassembly of the separate portions of the design, each of which by now has a high level of confidence at reaching its individual design goals.

1.5.7 Simulation

Before production commences in volume, confidence is needed that the design will be appropriate to go to market. It is often referred to as ‘prototyping’ and can be real or virtual. The distinguishing feature of this stage is that it is very high fidelity, as distinct from the analysis stage that was no more accurate than necessary.

Prototype vehicles, produced from non-representative tools and/or processes, are physical simulations instead of mathematical ones. The increasing use of ‘virtual’ prototyping obviates these physical prototypes except for those where an understanding of the man/machine interaction is necessary. One of several arenas where this remains true is the dynamics task.

Predictive models that have been a long time in preparation can be used to assess, virtually and in some detail, the behaviour of the whole design. Models prepared during the Synthesis activity are taken and re-used. It is in this arena that great strides have been made in terms of processing power, model re-use and inter-package integration over the last decade. Unfortunately, in the minds of some, these super elaborate models are all that is useful and anything less is simply worthless, passé and old fashioned. These are valuable models and have a crucial part to play in the process, but without a well-shaped concept design they are unwieldy white elephants. When used unthinkingly they become part of a rather 'Victorian' process in which designs are completed and then inspected for fitness-for-purposes; in the event of them being unfit, an iterative loop is commenced. Far more rapid would have been to have understood the question and to proceed toward the solution in a linear, non-looping fashion.

1.5.8 Confirmation

Sign-off testing is to be carried out on real vehicles that are as representative as possible. This stage should reveal no surprises, as changes at this stage are expensive.

1.5.9 Review

Once the design is successfully signed off, a stage that is frequently omitted is the review. What was done well? What could have been better? What technology do we wish we had then that might be available to us now? Since the most cost-effective analysis activity is to recall accurately and comprehend what has gone before, a well-documented review activity saves time and money in the next vehicle programme.

The process described is not definitive, nor is it intended to be prescriptive. It should, however, illustrate the difference between 'analysis' and 'simulation' and clearly distinguish them.

1.6 Computational methods

Whether the equations of motion have been derived by hand or delegated to a commercial software package, the primary goal when considering vehicle dynamics is to be able to predict the time-domain solution to those equations. Another important type of solution, the eigensolution, is discussed in Chapter 3.

Once the equations of motion have been assembled, they are integrated numerically. This is a specialised field in its own right. There are many publications in the field and it is an area rife with difficulties and pitfalls for the unwary. However, in order to successfully use the commercially available software products, some comprehension of the difficulties involved are necessary for users. Chapter 3 deals with some of the more common difficulties with some examples for the reader. By far the most dangerous type of difficulty is the 'plausible but wrong' solution.

Commercial analysts must studiously guard against the 'garbage in, gospel out' mentality that pervades the engineering industry at present.

The equations can be solved in a fairly direct fashion as assembled by the commercial package pre-processor or they can be subject to further symbolic manipulation before numerical solution. So-called 'symbolic' codes offer some tremendous computational efficiency benefits and are being hailed by many as the future of multibody system analysis since they allow real-time computation of reasonably complex models without excessive computing power. The prospect of a real-time multibody system of the vehicle solved on-board in order to generate reference signals for the generation-after-next vehicle control systems seems genuine.

1.7 Computer-based tools

Multibody systems analysis software has become so easy to use that many users lack even a basic awareness of the methods they are using. This chapter charts the background and development to the current generation of multibody systems analysis programs. While the freedom from the purgatory of formulating one's own equations of motion is a blessing, it is partly that purgatory that aids the analyst's final understanding of the problem. Chapter 2, Kinematics and Dynamics of Rigid Bodies, is intended as a reference and also as a 'launch pad' for the enthusiastic readers to be able to teach themselves the process of so-called 'classical' modelling.

Crolla (1995) identifies the main types of computer-based tools, which can be used for vehicle dynamic simulation, and categorises these as:

1. Purpose designed simulation codes
2. Multibody simulation packages, which are numerical
3. Multibody simulation packages, which are algebraic (symbolic)
4. Toolkits such as MATLAB

One of the major conclusions that Crolla draws is that it is still generally the case that the ride and handling performance of a vehicle will be developed and refined mainly through subjective assessments. Most importantly he suggests that in concentrating on sophistication and precision in modelling, practising vehicle dynamicists may have got the balance wrong. This is an important issue that reinforces the main approach in this book, which is to encourage the application of models that lead to positive decisions and inputs to the vehicle design process.

Crolla's paper also provides an interesting historical review that highlights an important meeting at IMechE headquarters in 1956, 'Research in automobile stability and control and tyre performance'. The author states that in the field of vehicle dynamics the papers presented at this meeting are now regarded as seminal and are referred to in the USA as simply 'The IME Papers'.

One of the authors at that meeting, Segel, can be considered to be a pioneer in the field of vehicle dynamics. His paper (Segel, 1956) is one of the first examples where classical mechanics has been applied to an automobile in the study of lateral rigid body motion resulting from steering inputs. The paper describes work carried out on a Buick vehicle for General Motors and is based on transferable experience of aircraft stability gained at the Flight Research Department, Cornell Aeronautical Laboratory. The main thrust of the project was the development of a mathematical vehicle model that included the formulation of lateral tyre forces and the experimental verification using instrumented vehicle tests.

In 1993, almost 40 years after embarking on this early work in vehicle dynamics, Segel again visited the IMechE to present a comprehensive review paper (Segel, 1993), 'An overview of developments in road vehicle dynamics: past, present and future'. In it he provides a historical review that considers the development of vehicle dynamics theory in three distinct phases:

Period 1 – Invention of the car to early 1930s
Period 2 – Early 1930s to 1953
Period 3 – 1953 to the then present (1993)

In describing the start of Period 3 Segel references his early 'IME paper' (Segel, 1956). In terms of preparing a review of work in the area of vehicle dynamics there is an important point made in the paper regarding the rapid expansion in literature that makes any comprehensive summary and critique difficult. This is highlighted by his example of the 1992 FISITA Congress where a total of 70 papers were presented under the general title of 'Total Vehicle Dynamics'. In 2013, searching the SAE website alone using 'vehicle dynamics' (in quotes, so as to preclude matches to only the word vehicle or the word dynamics) produces 2692 papers. There are no fewer than 98 standards produced by the same search.

Following Segel's historical classification of the vehicle dynamics discipline to date, the authors of this text suggest that we have now entered a fourth era that may be characterised by the use of engineering analysis software as something of a 'commodity', bought and sold and often used without a great deal of formal comprehension. In these circumstances there is a need for the software to be absolutely watertight (currently not possible to guarantee) or else for a small number of experts – 'champions' – within organisations to ensure the 'commodity' users are not drifting off the rails, to use a horribly mixed metaphor. This mode of operation is already becoming established within the analysis groups of large automotive companies where analysts make use of customised software programs such as ADAMS/Car, the Simpack Vehicle Wizard or the Dymola Vehicle Dynamics library. These programs have two distinct types of usage. At one level the software is used by an 'expert' with the experience, knowledge and skill and to customise the models generated, the types of simulation to be performed and the format in which selected results will be presented. A larger group of 'standard' users are then able to use the program to carry out suspension or full vehicle simulations assuming little or no knowledge of multibody systems formulations and solution methods. Standard users in many organisations are not full-time analysts but designers or development engineers whose remit includes using analytical tools to inform their opinions according to protocols imposed by the organisation.

1.8 Commercial computer packages

Before the evolution of multibody system programs, engineers analysed the behaviour of mechanisms such as cam-followers and four-bar linkages on the basis of pure kinematic behaviour. Graphical methods were often used to obtain solutions. Chace (1985) summarises the early programs that led to the development of the MSC ADAMS program. One of the first programs (Cooper et al., 1965) was KAM (Kinematic Analysis Method) capable of performing displacement, velocity and acceleration analysis and solving reaction forces for a limited set of linkages and suspension models. Another early program (Knappe, 1965) was COMMEND (Computer-Orientated Mechanical Engineering Design), which was used for planar problems.

By 1969, Chace (1969, 1970) and Korybalski (Chace and Korybalski, 1970) had completed the original version of DAMN (Dynamic Analysis of Mechanical Networks). This was historically the first general program to solve time histories for systems undergoing large displacement dynamic motion. This work lead in 1971 to a new program DRAM (Dynamic Response of Articulated Machinery) that was further enhanced by Angel (Chace and Angel, 1977).

Orlandea published two *American Society of Mechanical Engineers* (ASME) papers (Orlandea et al., 1976a, 1976b). These were a development of the earlier two-dimensional programs to a three-dimensional code but without some of the impact capability contained in DRAM at that time. This program went on to form the core of MSC ADAMS.

General-purpose programs have been developed with a view to commercial gain and as such are able to address a much larger set of problems across a wide range of engineering industries.

A number of other systems based on commercial software have at times been developed specifically for automotive vehicle modelling applications. Several of the larger vehicle manufacturers have at some time integrated MSC ADAMS into their own in-house vehicle design systems. Early examples of these were the AMIGO system at Audi (Hudi, 1988), and MOGESSA at Volkswagen (Terlinden et al., 1987). The WOODS system based on user-defined worksheets was another system at that time in this case developed by German consultants for Ford in the UK (Kaminski, 1990). Ford's Global vehicle modelling activities have since focused on in-house generated linear models and the ADAMS/Chassis™ (formerly known as ADAMS/Pre™) package, a layer over the top of the standard MSC ADAMS pre- and post-processor that is strongly tailored towards productivity and consistency in vehicle analysis.

When the first edition was published there were two leading general-purpose programs, MSC ADAMS and LMS DADS. They dominated the ground vehicle and aerospace markets. LMS DADS has morphed into a product called Virtual Motion and inside MSC ADAMS there has been an explosion of so-called 'Vertical' products, which integrate technology-specific utilities (such as 'wrapping' analysis for caterpillar tracks) with a dual mode software interface geared towards the champion/standard user split described previously.

In the meantime, new products such as Simpack, Dymola and Amesim have emerged as serious commercial general-purpose products (all were somewhat nascent at the time of the first edition) along with open-source codes such as the entire Modelica endeavour (upon which Dymola is built), MBDyn from the university of Milan, SimTK, Metex and so on. What has also emerged is that software that was traditionally for other purposes, such as Matlab Simulink, has begun to extend its reach and coverage such that many useful studies can be carried out entirely within it, without recourse to a ‘traditional’ multibody solver.

MADYMO is a program recognised as having a multibody foundation with an embedded non-linear finite element capability. This program has been developed by TNO in the Netherlands and complements their established crash test work with dummies. Recent developments in MADYMO have included the development of biofidelic humanoid models to extend the simulation of crash test dummies to ‘real-world’ pedestrian impact scenarios.

Tremendous advances in computing power were readily foreseeable in 2004 and remain so. A current workstation laptop has 32 GB of RAM (or 32 million Apollo Guidance Computers) serving four separate ‘cores’ — really separate computers sharing the box and supporting the kind of parallel computing that was spoken of in reverent tones when using Cray-II computers remotely in the early 1990s. Models regarded as awkwardly complex only 10 years ago are now entirely manageable. Tracked vehicles, for example, can be modelled with the track represented link-by-link, including the contact interaction with deformable terrain and all the vehicle wheels; such models are currently close to the limit of what is tolerable in a normal workflow but for the next edition such models may be solving in real time on a mobile phone app.

Blundell (1999a and b, 2000a and b) published a series of four IMechE papers with the aim of summarising typical processes involved with using a general-purpose multibody program to simulate full vehicle handling manoeuvres. The first paper provided an overview of the usage of multibody systems analysis in vehicle dynamics. The second paper described suspension modelling and analysis methodologies. The third paper covered tyre modelling and provided example routines for different tyre models and data. The fourth and final paper brought the series together with a comparative study of full vehicle models, of varying complexity, simulating a double lane change manoeuvre. Results from the simulation models were compared with measured test data from the proving ground. The overall emphasis of the series of papers was to demonstrate the accuracy of simple efficient models based on parameters amenable to design sensitivity study variations rather than blindly modelling the vehicle ‘as is’.

Crolla et al. (1994) also define two fundamental types of multiboby systems (MBS) program, the first of which is where the equations are generated in numerical format and are solved directly using numerical integration routines embedded in the package. The second, more recent type of MBS program formulates the equations in symbolic form and often uses an independent solver. The authors also describe toolkits as collections of routines that generate models, formulate and solve equations, and present results.

Other examples of more recently developed general-purpose codes formulate the equations algebraically and use a symbolic approach. Examples of these programs include MESA VERDE (Wittenburg and Wolz, 1985), AUTOSIM (Sayers, 1990), and RASNA Applied Motion Software (Austin and Hollars, 1992). Crolla et al. (1992) provide a summary comparison of the differences between numeric and symbolic code. As stated, MBS programs will usually automatically formulate and solve the equations of motion although in some cases, such as with the work described by Costa (1991) and Holt and Cornish (1992) and Holt (1994), a program SDFAST has been used to formulate the equations of motion in symbolic form and another program ACSL (Automatic Continuous Simulation Language) has been used to generate a solution.

Another customised application developed by the automotive industry is described in Scapaticci et al. (1992). In this paper the authors describe how MSC ADAMS has been integrated into a system known as SARAH (Suspension Analyses Reduced ADAMS Handling). This in-house system for the automotive industry was developed by the Fiat Research Centre Handling Group and used a suspension modelling technique that ignored suspension layout but focused on the final effects of wheel centre trajectory and orientation.

This leads nicely into another category of software available, the single-purpose tool. Unlike the general-purpose tools, which can build models of anything from door latches to spacecraft, some software is written specifically for modelling vehicle dynamics.

At Leeds University a vehicle-specific system was developed under the supervision of Crolla. In this case all the commonly required vehicle dynamics studies have been embodied in their own set of programs (Crolla et al., 1994) known as VDAS (Vehicle Dynamics Analysis Software). Examples of the applications incorporated in this system included: ride/handling, suspensions, natural frequencies, mode shapes, frequency response and steady state handling diagrams. The system included a range of models and further new models could be added using a pre-processor. Single-purpose programs are described as those where the equations of motion have been developed and programmed for a specific model. Model parameters can be changed but the model is fixed unless the program is changed and recompiled. A single-purpose program for passenger cars cannot be used for motorcycles, for example.

A typical example of this type of program would be AUTOSIM described by Sayers (1990), Sharp (1997) and Mousseau et al. (1992) which is intended for vehicle handling and has been developed as a symbolic code in order to produce very fast simulations. Other examples are the Milliken Research Associates VDMS program, which is a single-purpose model for use within the Matlab environment, and IPG Carmaker. For vehicles other than cars, BikeSim and TruckSim are both available.

Generally, single-purpose programs are specifically developed for a given type of simulation but often allow flexibility as to the choice and complexity of the model. An extension of this is where the equations of motion for a fixed vehicle modelling

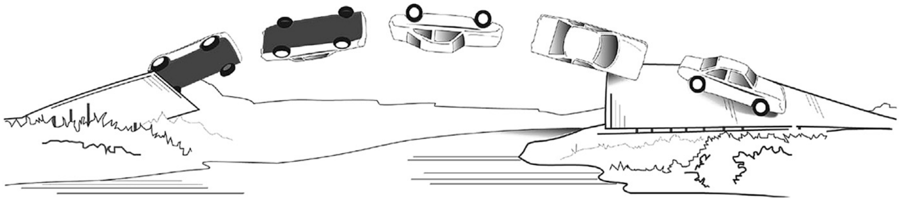

FIGURE 1.8

The Astro Spiral Jump.

approach are programmed and cannot be changed by the user such as the HVOSM (Highway-Vehicle-Object Simulation Model) developed by Raymond McHenry at Calspan in the mid 1960s. The program includes tyre and suspension models and can be used for impact studies in addition to the normal ride and handling simulations. HVOSM deserves a special mention for its contribution to the Astro Spiral Jump (Figure 1.8), a stunt used in the 1974 James Bond film 'The Man with the Golden Gun' that would have been more or less impossible to choreograph using traditional incremental stunt development methods.

The authors (Crolla et al., 1992) indicate that the University of Missouri has also developed a light vehicle dynamics simulation (LVDS) program that runs on a PC and can produce animated outputs. In the mid 1980s, Systems Technology, Inc. developed a program for vehicle dynamics analysis non-linear (VDANL) simulation. This program is based on a 13 degree of freedom, lumped parameter model (Allen et al., 1987) and has been used by researchers at Ohio State University for sensitivity analysis studies (Tandy et al., 1992).

More recently, programs such as ARAS 360 have emerged for vehicle dynamics simulation within the accident reconstruction sphere. ARAS 360 has a 15 degree-of-freedom vehicle model, non-linear tyre behaviour and a rich graphical environment including weather rendering and skid mark production.

The relative ease of computing the vehicle dynamics problem has lead to a number of novel applications for it. In widespread use in aviation, simulators are generating a lot of interest for the study of the human aspect of vehicle control. Real-time capable models that can complete their calculations in the same timescale as the world progresses, or faster, have become relatively common. Several of the commercial packages have a real-time capable implementation although this can depend greatly on the level of complexity selected. In general, single-purpose programs perform better than general-purpose programs in this arena but the relatively low complexity of the computational problem means that even general-purpose programs can be pressed into real-time use if the burden of graphical processing is offloaded to a dedicated computing resource. The development of compelling motion cueing is still somewhat incomplete with ground vehicle simulators, unlike aircraft simulators that have a different range of sensations to reproduce. Around 2000 a project was carried out on behalf of Prodrive by Harty for Evolution Studios in Cheshire in which a 50 Hz calculation rate produced excellent behaviour including non-linear tyre behaviour for a simulated vehicle on the Sony Playstation platform. The 'accurate' form of the model was not used for the final production release of the games since the phase delays it produced were too realistic (and hence too difficult) for many players to assimilate in a video game environment. A copy of the accurate form of the model is retained by Harty, along with a now-vintage Playstation.

For the Playstation, the tyre model was cut down to the absolute minimum complexity. This model (the 'Harty' model) is described in Chapter 5.

1.9 Benchmarking exercises

A detailed comparison between the various codes is beyond the capability of most companies when selecting an MBS program. In many ways the use of multibody systems has followed on from the earlier use of finite element analysis, the latter being approximately 10 years more mature as applied commercial software. Finite element codes were subject to a rigorous and successful series of benchmarks under the auspices of NAFEMS (National Agency for Finite Elements and Standards) during the 1980s. The published results provided analysts with useful comparisons between major finite element programs such as NASTRAN and ANSYS. The tests performed compared results obtained for a range of analysis methods with various finite elements.

For the vehicle dynamics community, Kortum and Sharp (1991) recognised that with the rapid growth in available multibody systems analysis programs a similar benchmarking exercise was needed. This exercise was organised through the International Association for Vehicle System Dynamics (IAVSD). In this study the various commercially available MBS programs were used to benchmark two problems. The first was to model the Iltis military vehicle and the second a five-link suspension system. A review of the exercise is provided by Sharp (1994) where some of the difficulties involved with such a wide-ranging study are discussed. An example of the problems involved would be the comparison of results. With different investigators using the various programs at widespread locations, a simple problem occurred when the results were sent in plotted form using different size plots and inconsistent axes making direct comparisons between the codes extremely difficult. It was also very difficult to ensure that a consistent modelling approach was used by the various investigators so that the comparison was based strictly on the differences between the programs and not the models used. An example of this with the Iltis vehicle would be modelling a leaf spring for which in many programs there were at the time no standard elements within the main code. Although not entirely successful the exercise was useful in being the only known attempt to provide a comparison between all the main multibody programs at the time. It should also be recognised that in the period since the exercise most of the commercial programs have been extensively developed to add a wide range of capability.

Anderson and Hanna (1989) have carried out an interesting study where they have used two vehicles to make a comparison of three different vehicle simulation methodologies. They have also made use of the Iltis, a vehicle of German design, which at that time was the current small utility vehicle used by the Canadian military. The Iltis was a vehicle that was considered to have performed well and had very different characteristics to the M-151 jeep that was the other vehicle in this study. The authors state that the M-151 vehicle, also used by the Canadian military, had been declared unsafe due to a propensity for rolling over.

Work has been carried out at the University of Bath (Ross-Martin et al., 1992) where the authors have compared MSC ADAMS with their own hydraulic and simulation package. The results for both programs are compared with measured vehicle test data provided in this case by Ford. The Bath model is similar to the Roll Stiffness Model described later in this book but is based on a force roll centre as described by Dixon (1987). This requires the vehicle to actually exist so that the model can use measured inputs obtained through static rig measurements, using equipment of the type described by Whitehead (1995). The roll-centre model described in this book is based on a kinematic roll centre derived using a geometric construction as described in Chapter 4, though there is little to preclude a force-based prediction by modelling the test rig on which the real vehicle is measured.

As a guide to the complexity of the models discussed in Ross-Martin et al. (1992), the Bath model required 91 pieces of information and the MSC ADAMS model although not described in detail needed 380 pieces of information. It is also stated in this paper that the MSC ADAMS model used 150 sets of non-linear data pairs that suggests detailed modelling of all the non-linear properties of individual bushes throughout the vehicle.

Limited studies continue for specific modelling challenges, such as that surrounding mobility for tracked vehicles on deformable terrain. Madsen discusses a comparison between the empirically formulated and widely used Becker soil model and a causally modelled granular soil environment in a package called Chrono::Engine (Madsen et al., 2010). He rather casually notes that a hardware-induced limit of one thousand million (a US billion) contact bodies might preclude modelling grains of sand and call for a slightly coarser approach; again we can be confident that this will probably no longer be an issue for the third edition of this book.

Since the IAVSD benchmarking exercise no new wide-ranging studies have been performed, which is interesting in its own right. It could be interpreted as meaning that most of the software is regarded as 'correct enough' for the applications to which it is put. It is also interesting to note a general shift in terms of the acceptance of predictive modelling such that there is no longer a widely held belief that it does not add value – many organisations have success stories to tell, and software companies carefully collate them to give confidence to new customers.

This leads to an interesting swing of the pendulum; it used to be a popular aphorism that 'nobody believes a simulation except the man who did it, and everyone believes a measurement – except the man who did it'. Currently though, it feels to the authors like some well-presented graphics can give predictive models a credibility out of all proportion to the estimated and uncertain data on which they are based and the often incomplete studies in which they are used.

The basic principle of science — that having formed a hypothesis one should diligently search for proof that it is untrue[8] appears to be cast aside in the rather convenient belief that the computer models are 'probably right' — when nothing of the sort is true. Basic aspects of self-doubt, such as convergence checking and input sensitivity checks, are often overlooked in a misplaced desire for productivity.

[8]Also known as 'Black Swan' search; one may produce as many white swans as one likes and while it is consistent with the hypothesis that all swans are white, it is not proof. It takes only one black swan to disprove the hypothesis completely. Black swans are alive and well in Australia.