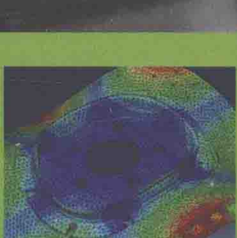
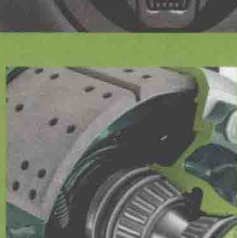
BRAKING OF ROAD VEHICLES

ANDREW DAY

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Preface

This book is intended to be an introduction to the science and engineering of road vehicle braking, and is based on lecture courses related to automotive chassis engineering, brakes and braking. Most significantly, the short course for industry on the 'Braking of Road Vehicles', which I have organised as part of my contribution to knowledge transfer and exchange between industry and academia since 1996 (the course itself started at Loughborough University in 1966 and I gave my first lecture on it in 1979), has brought me into contact with many expert practitioners who have given freely of their knowledge and time, and hundreds of delegates with their own questions and thirst for knowledge. I extend my thanks to all colleagues, companies and organisations who have helped me extend my knowledge in this way, and have named a few of them below.

Over the years road vehicle braking has become an increasingly broad and complicated field as its importance in road vehicle safety has been increasingly recognised and developed, and I have observed that whilst many engineers have very deep knowledge of detailed and highly specialised aspects of braking, the more general principles and practice of braking can be under-appreciated. The purpose of this book is therefore to provide this basic knowledge in a formalised way, present the principles and theory, explain the analyses and applications, and provide some interpretation and discussion of the principles and practice, while leaving the advanced topics to the specialists who are represented in the wealth of research literature that is available in the public domain. The first seven chapters set out the basic engineering theory and analysis for automotive brake and braking system design. The subsequent chapters present a closer look at some of the 'application-oriented' aspects of braking, including legislation and safety, testing, brake noise and judder, electronic braking, and finally a few case studies from my 37 years of endeavour in the field of automotive braking. The braking industry has its own way of analysing and presenting designs and data; wherever possible I have tried to adopt a generic approach, avoiding approaches, nomenclature and presentations that may be familiar to some but unknown to others. Readers may try to follow what I hope is the logical development of the subject matter in the first seven chapters, and then 'dip into' the other five. Alternatively they may wish to search for information relevant to their particular interest, but I recommend that at least they read Chapters 1 and 2, which contain some fundamentally important observations.

The book is dedicated to two Peters, Peter Newcomb and Peter Harding, who mentored and guided me many years ago in my introduction to road vehicle braking. The original *Braking of Road Vehicles* book, co-authored by Peter Newcomb and Bob Spurr, and published by Chapman & Hall in 1967, was the classic definitive introductory textbook on the subject. Peter Newcomb advised me throughout my PhD research and we worked together for many years on all aspects of braking, including the 'Braking of Road Vehicles' short course. Peter Harding was a gifted engineer and manager (and rock-climber) at Mintex Ltd., manufacturers of friction materials, and had the most remarkable knowledge of braking and friction materials gained from a lifetime in the industry. Much of the knowledge presented in this book started from them and has been accumulated by me over 37 years. Although I cannot always remember the original sources, where possible I have attempted to reference them.

My acknowledgements and thanks go to the following people and organisations:

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To many other people and organisations for information and diagrams that I have picked up over the years.

Andrew Day
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CHAPTER 1

Introduction

'Never start anything you can't stop' applies to many aspects of modern life but nowhere does this maxim apply more appropriately than to transport. For road vehicles, whether intended for personal or commercial use, it is surprising how performance data still appears to concentrate on the capability of the engine and powertrain to accelerate the vehicle, or to provide an attractive power-to-weight ratio to maintain speed, with scarcely a mention of the ability of the braking system to decelerate it quickly and safely. The conventional view of vehicle braking systems, even in the technologically advanced twenty-first century world of road transport, is that brakes are 'straightforward'; what could be simpler than pushing one material against another to create a friction force to absorb the energy of motion and slow the vehicle down?

Yet the braking system of a modern road vehicle is a triumph of technological advances in three distinct scientific and engineering disciplines. Firstly, materials science and engineering has delivered technologically advanced friction couples that form the heart of any road vehicle braking system. These advanced friction couples provide reliable, durable and consistent friction forces under the most arduous conditions of mechanical and thermal loading in operating environments where temperatures may exceed 800°C. The materials that make up these friction couples are in many ways quite environmentally sustainable; e.g. the cast iron for brake discs or drums is a relatively straightforward formulation which utilises a high proportion of scrap iron. The friction material includes in its formulation naturally occurring materials such as mineral fibres and friction modifiers, together with recycled components such as rubber in the form of tyre crumb.

Secondly, advanced mechanical engineering design has enabled high-strength braking system components to be optimised to deliver consistent and controllable braking torques and forces over a huge range of operational and environmental conditions. The use of computer-aided design and analysis methods has enabled stress concentrations to be identified and avoided, with the result that structural failures of brake components are unusual in any aspect of modern braking systems. The modern 'foundation brake' (i.e. the wheel brake rotor/stator unit) has been designed to dissipate the heat converted from the kinetic energy of the moving vehicle through the process of friction to the environment as quickly and effectively as possible. Design advances such as ventilated brake discs and sliding calipers have only been possible through the use of modern modelling and simulation techniques so that the underlying scientific principles can be applied effectively.

Thirdly, close and accurate control of braking systems and components through electronics and software engineering has moved braking firmly into the area of active vehicle safety. Forty years ago, Antilock Braking Systems (ABS) demonstrated the safety benefits of maintaining directional control while braking under high deceleration and/or low adhesion conditions. It quickly became clear that 'intelligent' control of the braking system had much more to offer, ranging from traction control where the brake on a spinning wheel could be applied to match the wheel speed to the available road speed or traction availability, through electronic braking distribution to maximise the brake torque depending on the adhesion conditions at each tyre/road interface, and most recently to stability control (ESC) where judicious application of individual wheel brakes according to carefully developed and extremely sophisticated control algorithms could help mitigate the effect of potentially hazardous manoeuvres. It is worth noting that this required a change in legislation, in the sense that non-driver-initiated brake application, or 'intervention' as it is known, had to be permitted before such active safety could be legally incorporated in production vehicles.

However, alongside the remarkable technology advances that have emanated from these three areas of endeavour, it should be noted that the road vehicle braking system is still a remarkably low-cost part of the overall vehicle, and the reliability and maintainability of the braking system on any modern road vehicle is extremely high. Despite the complexity and sophistication of the braking system, and the often environmentally challenging conditions under which the brakes have to operate, routine maintenance is mostly all that is required, and when replacement of, for example, the brake pads or discs is required, the correct parts can be obtained and fitted quickly almost anywhere in the world. The need for regular and appropriate maintenance of any vehicle's braking system must not be underestimated; 1.7% of road accidents in Germany in 2009 were attributed to faulty brakes (ECE, 2012).

Almost since the dawn of wheeled road transport, friction between a rotor (attached to the wheel) and a stator (attached to the vehicle body, chassis or axle) has been utilised in some form to provide controlled vehicle retardation. Other methods have historically been employed, e.g. dragging a heavy object on the road behind the vehicle, or simply steering the vehicle into a conveniently positioned obstacle, but these do not offer much in the way of sustainability, consistency or reliability. Using the vehicle's engine to provide a retarding torque (engine braking) is standard practice in commercial vehicles as a form of 'retarder' in the transmission to generate braking torque. Aerodynamically designed 'air brakes' are found to be effective in taking on some of the duty of the friction brakes at high speeds in high-performance cars. But the most significant recent development in non-friction-based road vehicle braking is regenerative braking. For many years it has been accepted that the kinetic energy of a moving vehicle is dissipated into the environment during braking. It is only with the world's current concerns over CO_2 emissions and limited fossil fuel reserves that this has been challenged.

The braking system of any road vehicle is subject to extensive legislative standards and requirements in many regions of the world. In this book the legislative framework considered is the European Union (UN) Legislation and Regulations, although comparison with the US legislation is made where appropriate. EU law states that all road vehicles are required to have a working braking system that meets the legislative requirements. Included in the braking system requirements are 'service' and 'secondary' braking systems so that the vehicle can be safely brought to rest even in the event of the failure of one part of the system, and a 'parking brake' that can hold the vehicle safely on a specified incline. In Europe, vehicle manufacturers have to demonstrate that their vehicle meets the design and performance standards specified in the UN Regulations through a process of Type Approval. Once a vehicle is sold, the responsibility passes to the owner or user of the vehicle to ensure that the vehicle's braking system continues to meet legal requirements; usually this takes the form of a regular compulsory examination of the vehicle. The design and performance standards associated with Type Approval are regarded as minimum standards, and most vehicle manufacturers have their own 'in-house' standards that exceed the 'legal requirements', often by a considerable margin. For example, UN Regulation 13H (UN, Feb 2014) states that the minimum service braking performance defined by the 'Type-0 test with engine disconnected' for a passenger car (category M_1) is a mean deceleration of 6.43 m/s^2 for a driver pedal effort (brake pedal force) of between 6.5 and 50 daN. Car manufacturers would typically design for substantially more vehicle deceleration for this level of pedal effort, but have to bear in mind the requirement for the secondary braking system to provide a deceleration of not less than 2.44 m/s^2 within the same range of pedal effort. Pedal effort is important because of the large range of physical capability of different drivers. Likewise, the parking brake is covered by a set of legislative requirements and standards, including operating force.

Fundamental to the design of a braking system for a road vehicle (under UN regulations) is that a brake is required at every road wheel. The only exception is light trailers (Category O_1: trailers with a maximum mass not exceeding 0.75 tonnes), which do not need to be fitted with wheel brakes, relying instead upon the brakes of the towing vehicle. In commercial vehicle parlance, the brake unit at the wheel is known as the 'foundation brake'. This term, which is applied exclusively to friction brakes, is used throughout this book to define the wheel brake unit for all vehicles: commercial vehicles, passenger cars, trailers, etc. The function of the foundation brake is to generate a retarding torque (i.e. one that opposes the direction of rotation of the wheel to which it is attached), which is proportional to the actuation force applied. There are two distinct types of automotive foundation brake in common use today, namely the 'drum' brake (Figure 1.1(a)), where the stators are brake shoes fitted with friction material linings that are expanded outwards to press against the inner surface of a rotor in the form of a

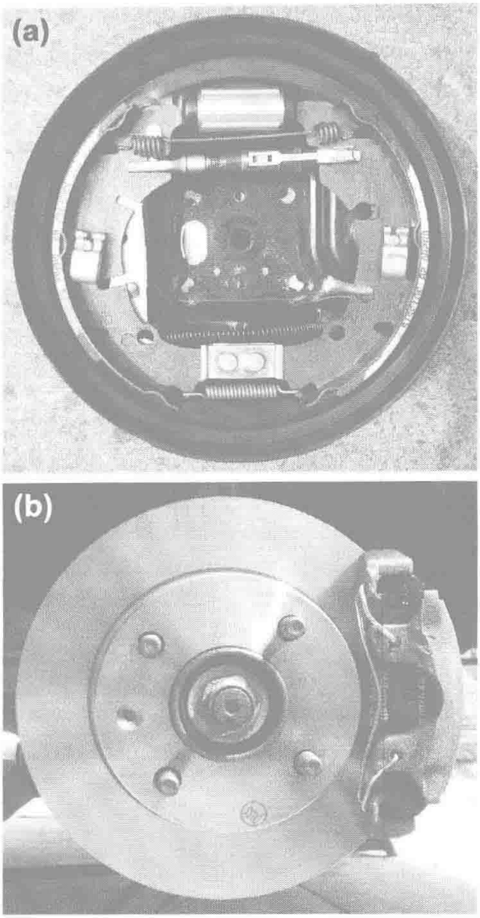

Figure 1.1: (a) Drum Brake. (b) Disc Brake.

brake drum, and the 'disc' brake (Figure 1.1(b)), where the stators are brake pads that are clamped against the outer surfaces of a rotor in the form of a brake disc. Included in the definition of 'foundation brake' are the mounting fixtures such as the 'anchor plate', (also termed 'torque plate', 'spider', or 'reaction frame'), which is firmly bolted to the axle or steering knuckle. The mechanism by which the force provided by the actuation system is applied to the stator elements (pads or shoes) is also considered as being part of the foundation brake.

The brake actuation system comprises the mechanical, electrical and electronic components, which recognise and interpret the 'driver demand', e.g. from the movement of the brake pedal and/or the force applied by the driver to it, and convert it into forces applied to the individual foundation brakes to generate the required retarding torque. The basic brake actuation system transmits the force on the brake pedal through various mechanical connections to the foundation brake. These mechanical connections may take the form of cables, rods and linkages, hydrostatic, hydraulic, or pneumatic systems. They fall into two distinct categories, namely those that rely upon the 'muscular' energy of the driver, and those that rely upon a separate energy source to provide the actuation force which is under the control of the driver. The former usually has a 'servo' or 'booster' in the system to provide power assistance in order to reduce pedal efforts (termed 'power brakes' in the USA), and tends to be used on lighter vehicles such as passenger cars. The latter type of system is used on heavy commercial vehicles in the form of pneumatic or 'air brake' systems, although power hydraulic braking systems are also fitted to some types of commercial vehicle, sometimes in the form of combined 'air over hydraulic' systems. Over the last 25 years the 'mechanical' basis of brake actuation systems has been increasingly augmented by electromechanical technology and electronic control to provide the 'intelligent' control that is such a valuable safety-enhancing feature of modern road vehicle braking systems. This can range from electromechanical handbrake actuation through Electronic Brakeforce Distribution (EBD) at each wheel to full Electronic Stability Control (ESC).

The fundamental scientific principles of the design and analysis of foundation brakes and actuation systems were established many years ago. The required basic performance of the braking system for any road vehicle is always specified in terms of the required brake force at each wheel. This depends upon the design specification of the vehicle, so this is always the starting point for road vehicle braking system design. The design of the foundation brake and the actuation system components, although included in this book, is usually completed in detail by the specialist, and from the vehicle manufacturer's point of view braking system design has tended to become a process of specification and selection. Many vehicle manufacturers have in the past contracted the braking system design out to 'full service suppliers' who have the specialist skills and knowledge to design and deliver a vehicle braking system that meets the vehicle manufacturer's requirements. But increasingly, the importance of the braking system to the overall safety of the vehicle, the need for close integration of the braking system with other vehicle control and management systems, and the sensitivity of the customer to the braking system performance have encouraged most vehicle manufacturers to retain a substantial interest in the braking system design. This has meant that a detailed knowledge of brakes and braking systems is valuable to the vehicle manufacturer and it is the purpose of this book to address this.

The end user of the braking system on any vehicle is the driver, whose expectations are quite straightforward; he or she should be able to apply the brakes in a smooth and controllable manner to generate an equally smooth and controllable vehicle deceleration that is consistent throughout all conditions of vehicle operation and environments. In the foundation brake, this requires remarkable stability in the frictional performance of the brake friction pair, namely the friction material and the rotor, over a wide range of operational and environmental conditions. Most drivers are very sensitive to changes in the braking response of the vehicle, so 'brake pedal feel' is a major attribute in a successful road vehicle to the extent that poor brake response can adversely affect vehicle sales. Drivers (and passengers and other road users) generally do not like their brakes to make a noise, or create uncomfortable vibration while applied, so attention to the noise and vibration aspects of a brake installation on a vehicle is very important for the vehicle manufacturer to avoid customer dissatisfaction.

Because of the concerns over the sustainability of road transport, friction braking is now increasingly seen as wasteful, and strategies for the speed control of road vehicles without using the foundation brakes are increasingly being developed and employed in the form of regenerative braking. Regenerative braking requires technology by which kinetic energy can be converted to and from a more easily storable form of energy, and a device to which that energy can be transferred, stored and recuperated. Some systems are relatively easily included in existing powertrain technology, e.g. alternators that charge only on engine overrun, but the technology to achieve significant deceleration by regenerative braking is expensive and adds mass to the vehicle. 'Hybrid' vehicle technology has shown over the last 20 years how regenerative braking can be combined with friction braking to create effective 'mixed-mode' braking systems. Mostly these are based on electric motor/generator and battery technology, but some hydraulic systems and mechanical (flywheel) systems have also been explored. Because the foundation brake and regenerative braking systems have to work together, their integrated operation or 'blending' has to be transparent to the driver because of the sensitivity previously noted. This presents a major challenge to the vehicle chassis system engineers. Nevertheless, mixed-mode braking technology is progressing and already European legislation has been rewritten (UN, Mar 2014, Feb 2014) to accommodate developments in mixed-mode braking systems for road vehicles.

This book covers the design, implementation, and operation of brakes and braking systems for cars and commercial vehicles with associated trailers, which represent the majority of road vehicles. The principles described do apply to other types of road vehicle, though for some other types (e.g. motorcycles) specific aspects may be significantly different to those presented here. Examples of analyses and calculations are included, together with some examples of 'things that can go wrong' and likely causes. The book starts with a consideration of the science and technology of friction as applied to friction materials and vehicle foundation brakes; this is because an understanding of friction is considered to be fundamentally important in effective road vehicle braking system design. The decelerating road vehicle, including the specific configurations of two-axled rigid vehicles and multi-axle vehicle and trailer combinations, is then analysed to establish an understanding of the requirements of the braking system to achieve the