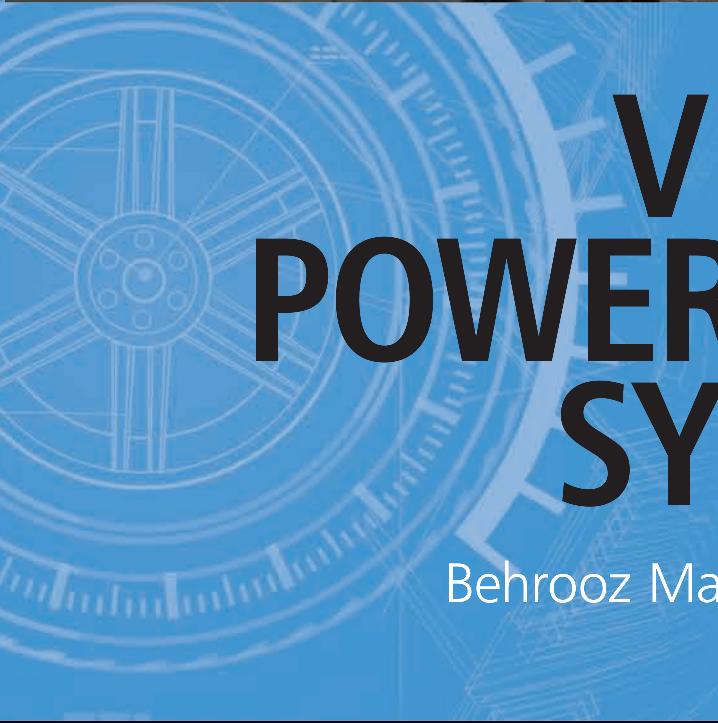


VEHICLE POWERTRAIN SYSTEMS

Behrooz Mashadi | David Crolla

WILEY

VEHICLE POWERTRAIN SYSTEMS

VEHICLE POWERTRAIN SYSTEMS

Behrooz Mashadi
Iran University of Science and Technology

David Crolla
University of Sunderland, UK

WILEY

A John Wiley & Sons, Ltd., Publication

This edition first published 2012
© 2012 John Wiley & Sons, Ltd

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

MATLAB® is a trademark of The MathWorks, Inc. and is used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB® software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB® software.

Library of Congress Cataloging-in-Publication Data

Mashadi, Behrooz.
Vehicle powertrain systems / Behrooz Mashadi, David Crolla.
p. cm.
Includes bibliographical references.
ISBN 978-0-470-66602-9 (cloth) – ISBN 978-1-119-95836-9 (ePDF) – ISBN 978-1-119-95837-6 (oBook) – ISBN 978-1-119-96102-4 (ePub) – ISBN 978-1-119-96103-1 (Mobi)
1. Automobiles–Power trains. 2. Automobiles–Dynamics. I. Crolla, David A. II. Title.
TL260.M37 2012
629.25'2–dc23 2011027302

A catalogue record for this book is available from the British Library.

Set in 9/11pt Times New Roman by Thomson Digital, Noida, India

This book is dedicated to Professor David Crolla who passed away unexpectedly while the book was in production. David led an unusually full and productive life both in work and play, achieving great success and popularity. David was a leading researcher, an inspiring teacher, an excellent supervisor of research postgraduates and a friend to many. David's energy, enthusiasm and irrepressible humour made a lasting impression on me and everyone who knew him. He is sorely missed and his essential contribution to the publication of this book will always be remembered.

Contents

6 Driveline Dynamics 387

7 Hybrid Electric Vehicles 425

About the Authors

Behrooz Mashadi is an Associate Professor in the Department of Automotive Engineering, Iran University of Science and Technology (IUST), Tehran, Iran. He received his BSc and MSc in Mechanical Engineering from Isfahan University of Technology (IUT), Isfahan, Iran, and his PhD degree in Vehicle Dynamics Engineering from the University of Leeds, in 1996 under the supervision of Professor D. A. Crolla. He was then engaged in several R&D projects in the automotive engineering industry and joined the academic staff at IUST in 2002.

He has developed and taught a wide range of courses for undergraduate and postgraduate students in the field of Automotive Engineering. He served as Deputy for Education in the Department of Automotive Engineering and is currently Deputy of the Automotive Research Centre at IUST, which is the leading centre for automotive R&D in Iran.

His current research interests include vehicle powertrain systems, hybrid propulsion systems, vehicle dynamics, vehicle modelling, simulation and control. He has presented and published over 100 papers in journals and conferences. He also serves on the editorial board of several international journals.

David Crolla, FREng, was a Visiting Professor of Automotive Engineering at the Universities of Leeds, Sunderland and Cranfield. After graduating from Loughborough University, he first worked as a research engineer in off-road vehicle design, and then joined the University of Leeds (1979–2001) becoming head of the Mechanical Engineering Department. His research interests included vehicle dynamics, chassis control systems, powertrain systems, suspensions and terramechanics, and he had published and presented over 250 papers in journals and conferences.

His activities included research in low carbon vehicles, industrial short courses in vehicle dynamics and chassis control, and engineering consultancy, for example, the BLOODHOUND SSC 1000mph land speed record attempt.

He was Editor-in-Chief of the world's first *Encyclopedia of Automotive Engineering* to be published in 2013.

Preface

In writing this book, we have aimed it at the needs of both students and practising engineers in the automotive industry. For engineering students, we hope we have provided a sound explanation of the principles behind the design of vehicle powertrain systems. For practising engineers, we have tried to provide a comprehensive introduction to the subject area, which will set the scene for more specialized texts on, for example, engines, transmissions or hybrid electric components.

The book has arisen from our combined teaching experiences at a range of institutions including the Iran University of Science and Technology (IUST), Tehran, and the Universities of Leeds, Sunderland and Cranfield. We have attempted to incorporate two important themes which distinguish our book from other texts:

1. The inclusion of numerous worked examples and the provision of a MATLAB® code for many of the problems.
2. A systems approach to powertrain design – focusing on the integration and interactions of all the components, e.g. engine, transmission final drive, wheels and tyres – in analyzing the overall vehicle performance.

Our experience of teaching engineering students suggests that one of the most useful ways of learning engineering principles is through actually doing problems oneself. Hence, we have tried to provide a wide range of examples together with worked solutions, often with an accompanying MATLAB code. We hope that readers will run these short programmes themselves and modify them to examine other performance issues.

The term 'systems approach' is widely used in engineering but is not always clarified in the particular context. Here, we simply mean that in order to understand vehicle performance, it is necessary to analyze all the powertrain components together and examine how they interact, and how the designer tries to integrate them in a coordinated way. Our experience suggests that there are relatively few texts which deal comprehensively with this critical aspect of integration.

At the time of writing, there is considerable pressure on the automotive industry to minimize energy consumption and reduce global emissions. This has led to a huge upsurge in interest in alternative powertrain systems – and the development of a range of electric and hybrid electric vehicles. However, consumers do not appear to be willing to compromise some of the traditional aspects of vehicle performance, e.g. acceleration, speed, etc. in the interests of overall energy consumption. Drivability remains a key commercial issue and there is a demand for vehicles which are 'fun-to-drive'. Hence, the design challenge continues to involve a compromise between vehicle performance and energy usage. We have tried in this book to provide a comprehensive coverage of both these – often conflicting – aspects of vehicle behaviour.

Vehicle Powertrain Systems is accompanied by a website (www.wiley.com/go/mashadi) housing a solution manual with detailed explanations for the solution methods of more than a hundred exercises in this book. The solutions of the majority of the problems are carried out in MATLAB environment and the program listings are also provided. In addition to the worked examples of the book itself, the website offers invaluable guidance and understanding to students.

Finally, we would like to thank all our colleagues and friends over the years who have contributed in some way or influenced us in writing this text.

Abbreviations

2WD	2-wheel drive
4WD	4-wheel drive
AC	alternating current
AFR	air-fuel ratio
Ah	amp-hour
AMT	automated manual transmission
AT	automatic transmission
BAS	belted alternator starter
BD	block diagram
BDC	bottom dead centre
BLDC	brushless DC
BMEP	brake mean effective pressure
BMS	battery management system
BSFC	brake specific fuel consumption
CAFE	corporate average fuel economy
CI	compression ignition
CO_2	carbon dioxide
COP	conformity of production
CPP	constant power performance
CSM	charge sustaining mode
CTP	constant torque performance
CVT	continuously variable transmission
DC	direct current
DCT	dual clutch transmission
deg.	degree
DOF	degree of freedom
DOH	degree of hybridization
EC	eddy current
ECU	engine control unit
EFCC	Efficient Fuel Consumption Curve
EGR	exhaust gas recirculation
EM	electric motor
EMS	engine management system
EOP	engine operating point
EPA	Environmental Protection Agency
EREV	extended range electric vehicle
EUDC	extra-urban European driving cycle
EV	electric vehicle

FBD	free body diagram
FC	fuel consumption
FCVs	fuel cell vehicles
FEAD	front engine accessory drive
FEM	finite elements methods
FTP	Federal Test Procedure
FTP	fixed throttle performance
FWD	front wheel drive
GDI	gasoline direct injection
HC	hydrocarbons
HCCI	homogeneous charge compression ignition
HEV	hybrid electric vehicle
IC	internal combustion
ICE	internal combustion engine
IMEP	indicated mean effective pressure
I/O	input/output
ISG	integrated starter-generator
ISO	International Standard Organization
IVT	infinitely variable transmission
kg/J	kilogram per joule
kWh	kW-hour
l	litre
LCV	low carbon vehicle
LS	low speed
MAP	manifold absolute pressure
MC	motor controller
MCU	motor control unit
MG	motor/generator
MPa	mega Pascal
MPD	mechanical power distribution
MPI	multi-point (port) injection
MT	Magic Torque (formula)
MT	manual transmission
NEDC	New European Driving Cycle
NOx	oxides of nitrogen
NRF	no-resistive-force
NVH	noise, vibration and harshness
OOL	optimal operating line
PCP	pedal cycle performance
PGS	planetary gear set
PHEV	plug-in hybrid electric vehicle
PID	proportional integral derivative
PSD	power split device
RMS	root mean square
rpm	revs per minute
RWD	rear wheel drive
SCU	supervisory control unit
SFG	single flow graph
SI	spark-ignition
SOC	state of charge

SPH	series-parallel hybrid
TA	type approval
TAD	torque amplification device
TBI	throttle body injection
TC	torque converter
TDC	top dead centre
THS	Toyota Hybrid System
TPS	throttle position sensor
VVT	variable valve timing
Wh	Watt-hour
WOT	wide-open throttle

1

Vehicle Powertrain Concepts

1.1 Powertrain Systems

Over the past 100 years, vehicles have changed our lives; they have provided mobility which we exploit in all our commercial activities around the globe and they have also provided millions of us with new opportunities afforded by personal transportation. At the very heart of vehicle design is the powertrain system; it is the engineering of the powertrain system which provides the driving force behind the mobility.

The output from the power source – to date, dominated by the internal combustion (IC) engine – is controlled by a transmission system and driveline to deliver tractive effort to the wheels. And all these components, collectively referred to as the powertrain system, are controlled by the driver. Drivers, who are also viewed as discerning customers by the vehicle manufacturers, have a range of performance criteria: acceleration, top speed, fuel economy, gradeability, and towing capacity are some of the more obvious quantitative features. But subjective judgements such as driveability, fun to drive, refinement and driving pleasure play a huge part in the commercial success of vehicles. On the other hand, society imposes different performance demands – with a huge recent emphasis on emissions and CO_2 usage of vehicles. And governments have gone as far as imposing overall emissions control targets on manufacturers' fleets of vehicles.

In order to meet all these conflicting demands, engineers must master the complete powertrain system. If there is one underlying theme to this book, it is that in order to understand vehicle mobility, one must analyze the entire system together – driver, engine, transmission, driving cycles, etc. The aim of this chapter is to provide the background to this theme.

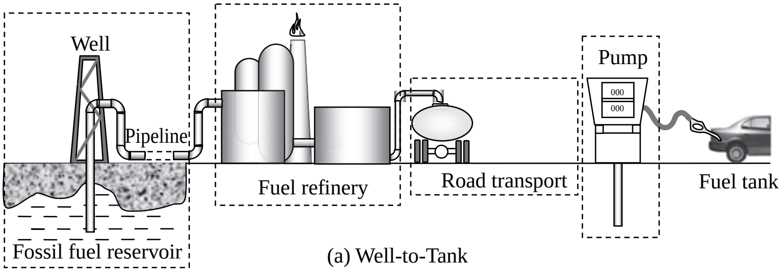
1.1.1 Systems Approach

The key issue at the heart of this textbook is to adopt a systems approach to vehicle powertrain design. In simple terms, this means collecting all the individual components in the powertrain – or drivetrain as it is sometimes called – and analyzing how they combine and interact. The ultimate aim is, of course, to predict the overall vehicle behaviour in terms of speed, acceleration, gradeability, fuel economy, etc.

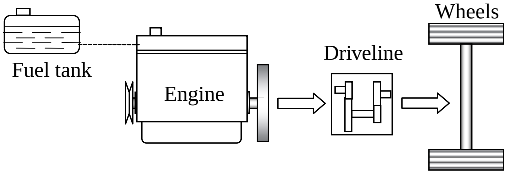
First, the behaviour of the powertrain components is analyzed – and then these components are put together as a complete system to capture the overall vehicle driveline from the prime mover, traditionally, an IC engine, through the transmission – clutch, gears, differential, etc. – to the final drive at the wheels. The important theme is that it is only by taking a system-level view of the powertrain that the vehicle designer can achieve the desired goals of vehicle performance. In a systems approach to any problem, it is important at the outset to define the system boundaries. So, for example, if we wish to study the overall use

---

Vehicle Powertrain Systems, First Edition. Behrooz Mashadi and David Crolla.



(a) Well-to-Tank



(b) Tank-to-Wheels

Figure 1.1 Overall energy conversion process in vehicle transportation – the Well-to-Wheels idea

of energy in passenger car transportation, the system would look like that shown in Figure 1.1 – in which the energy is tracked from its original source through to its final usage in propelling a vehicle. This overview is important in the context of powertrain system design, and is now commonly referred to as the Well-to-Wheels analysis of energy consumption.

1.1.2 History

There are lots of fascinating books describing the historical development of the automobile. It is not our intention in this book to dwell upon the history of automotive engineering; however, there are some interesting observations which set the scene for our analysis of powertrain systems.

In 1997, the SAE published an informative book [1] on the history of the automobile to celebrate its centenary. Each chapter was written by an invited US expert and all the powertrain components – powerplant (engine), transmissions, tyres, etc. – were covered. From the viewpoint of engineering innovation, it is very clear that there was plethora of innovative designs published in the late 1800s to early 1900s – but their practical exploitation was only realized decades later when material properties and mass manufacturing techniques had improved. For example, there were plenty of designs for what we consider fairly complex engineering components – automatic transmissions and continuously variable transmissions – patented in this period, but they had to wait several decades before they could be exploited commercially. The historical development of manufacturing, mass production and the economic context of automobile engineering is given in an excellent textbook by Eckerman [2].

In relation to powertrain systems, the two major components – the IC engine and the transmission have been reviewed from a historical perspective. The title of Daniels' book *Driving Force* [3] summarizes the role of the IC engine as the dominant power source for vehicles during the twentieth century. He presents a comprehensive overview of the detailed engineering development of engine design from its crude beginnings in 1876 as the stationary Otto engine to its current state of the art, characterized as much by sophisticated control systems as by mechanical design.

Some engineers would argue that developments in transmission design were equally important over the twentieth century. Taking the systems viewpoint, one would have to agree with this argument – since the IC engine power is only available over a limited speed range, and hence the transmission is crucial in

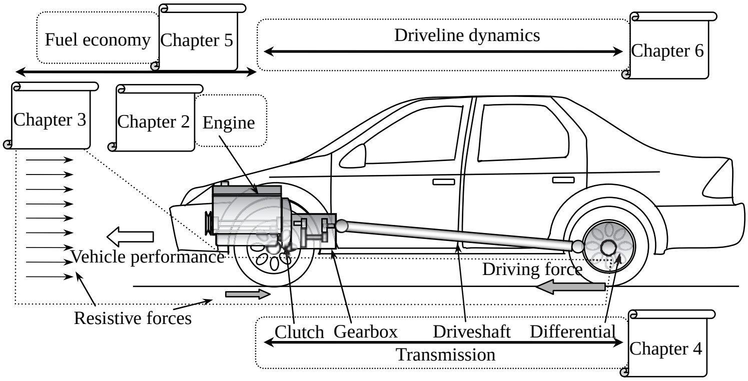


Figure 1.2 Overview of vehicle powertrain system and related book chapters

transforming it into usable power at the wheels. Gott [4] traces the history of engineering developments in transmissions – albeit with a bias towards the US preference for automatic transmissions. This review does, however, reinforce the systems approach since the control of the transmission must be totally integrated with the engine management control.

This holistic approach, in which all the interacting parts of the powertrain are considered together, leads to the idea of system optimization. For example, while it is clearly important to optimize the design of individual components, such as the engine and transmission, the overall aim must be that they are matched together as an integrated system.

1.1.3 Conventional Powertrains

This book concentrates mainly on what are commonly referred to as conventional powertrains – in which an IC engine drives the vehicle wheels through a transmission, incorporating a gearbox and final drive unit. A typical structure for a front-engined, rear wheel drive (RWD) car is shown in Figure 1.2, with a notation of how the chapters in this book are mapped on to the powertrain system. The most common layout for small passenger cars is front-engined, front wheel drive (FWD) but the principles associated with powertrain analysis are exactly the same.

The world's total population of cars and light trucks was estimated in 2009 at around 900 million, with a production of new cars and light trucks of about 61 million in the same year. The vast majority of these – more than 99% – employ conventional powertrains as described above. Hence, despite the enormous interest from 2000 onwards in alternative powertrains, described under the general heading of Low Carbon Vehicles (LCVs), it is clear that the principles of analysing and understanding conventional powertrain systems as described in this textbook will certainly be of interest for several more decades.

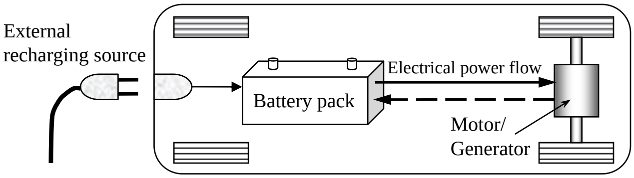
1.1.4 Hybrid Powertrains

During the late 1800s and early 1900s when engineers became fascinated with the opportunities for personal transportation provided by the motor car, there were three competing technologies for the powerplant – steam, electric and petrol. Each of these had their own merits and disadvantages, and it was not at all clear at the time which was likely to dominate in the longer term. In fact, a 1900 census in the eastern US states [5] showed that each of these technologies shared about a third each of the emerging market – however, horse-drawn carriages still dominated in terms of total vehicles!

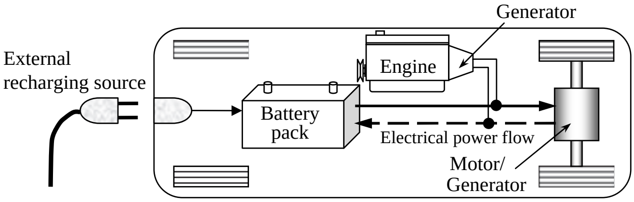
Steam had a longer history of development and there was no problem installing sufficient power to give good performance. But fuel economy was poor, the boiler needed firing up prior to a journey and both water storage and usage were problems. Electric vehicles looked extremely promising – they were quiet, clean and remarkably easy to operate. Range was the major problem limited by the available energy storage in the battery – a problem which remains to this day! Gasoline cars in that period were less well developed and appeared extremely troublesome – they were difficult to start and when running they were noisy, dirty and pretty unreliable. But their fundamental advantage – which of course is obvious now – was the energy density of gasoline which was about 300 times better than a lead-acid battery. This meant it was worthwhile investing in the engineering refinement of the gasoline-based powertrain – and this approach of relentless development and refinement has continued to the present day.

Given these discussions at the time about the best way forward for the automobile powerplant, it is not surprising that several forward-thinking engineers have suggested combining two powerplants in order to extract the benefits of each – and hence, the notion of a hybrid vehicle was born around the turn of the nineteenth century. They were not called ‘hybrid’ at the time, but it is nevertheless remarkable that, for example, the 1902 Woods gas-electric car [5] did realize the potential of what we now know as a series-electric hybrid layout. The vehicle was driven by a motor which doubled as a generator, it could run on battery power alone at low speeds, the downsized gasoline engine could be used to charge the battery, and it featured regenerative braking.

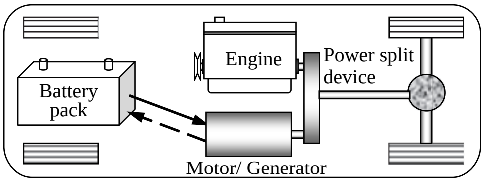
Although there are a substantial number of different powertrain architectures for hybrid vehicles, at the time of writing this book in 2011, three are of particular interest, all linked to commercially available vehicle models. These three types are summarized in Figure 1.3 and are:



(a) Plug-in electric vehicle



(b) Electric vehicle with range extender and plug-in facility



(c) Hybrid electric vehicle – tractive power provided by engine, motor or a combination of both

Figure 1.3 Three types of typical hybrid/electric vehicle architectures available in 2011

(a) plug-in electric vehicle (EV), e.g. Nissan Leaf;
(b) EV with range extender, e.g. Chevrolet Volt;
(c) hybrid electric vehicle (HEV), e.g. Toyota Prius

Chapter 7 in this book introduces the highly topical subject of hybrid vehicle powertrains. It is not intended to provide a comprehensive treatment of the rapidly changing subject of hybrid vehicle technology – many excellent texts have already been written on this topic and they are referenced at the end of Chapter 7. Rather, the chapter is intended to show how the same principles of powertrain systems analysis, which are the core of this textbook, can be applied to different technologies. The aim is to show how the systems approach to the analysis of so-called conventional powertrain components can readily be applied to powertrains built up of different components such as batteries, motor-generators, fuel cells, super-capacitors, etc.

1.2 Powertrain Components

The components in the powertrain are described in detail in each of the following chapters in the book – and references for further reading of the best books are also provided. Needless to say, all these components are subject to relentless efforts to improve their performance – efficiency, emissions control, refinement – as well as their overall cost effectiveness. The most recent trends in powertrain component engineering are summarized below.

1.2.1 Engine

- Stratified charge combustion
- Lean burn combustion
- HCCI (homogeneous charge compression ignition) combustion
- Variable valve timing
- Supercharging or twin-charging (when coupled with a downsized engine)
- Turbocharged direct injection diesel engines
- Gasoline direct injection petrol engines
- Common rail diesel engines
- Variable geometry turbocharging.

1.2.2 Transmission

- Lower-friction lubricants (engine oil, transmission fluid, axle fluid)
- Locking torque converters in automatic transmissions to reduce slip and power losses in the converter
- Continuously variable transmission (CVT)
- Automated manual gearbox
- Dual clutch gearbox
- Increase in the number of gearbox ratios in manual or automatic gearboxes.

1.2.3 Vehicle Structure

- Reducing vehicle weight by using materials such as aluminium, fibreglass, plastic, high-strength steel and carbon fibre instead of mild steel and iron.
- Using lighter materials for moving parts such as pistons, crankshaft, gears and alloy wheels.
- Replacing tyres with low rolling resistance models.

1.2.4 Systems Operation

- Automatically shutting off engine when vehicle is stopped.
- Recapturing wasted energy while braking (regenerative braking).
- Augmenting a downsized engine with an electric drive system and battery (mild hybrid vehicles).
- Improved control of water-based cooling systems so that engines reach their efficient operating temperature sooner.

1.3 Vehicle Performance

Ever since the first usable road vehicles appeared on the roads – built by, for example, Daimler, Benz, Peugeot and Panhard & Levassor in the 1890s and 1900s – people have quoted performance figures as a means of comparing vehicles. In the first instance, these were usually top speed and range; then came other performance measures as more powerful engines were installed – acceleration, gradeability and towing performance. Performance could be predicted based on very simple models using Newton's Second Law of Motion. For example, in Kerr Thomas' 1932 book [6], a chapter on the 'Mechanics of a Moving Vehicle' shows how to calculate speeds and accelerations based on knowledge of the engine torque and speed characteristics, gearbox ratios and estimates of the rolling resistance and aerodynamic drag terms.

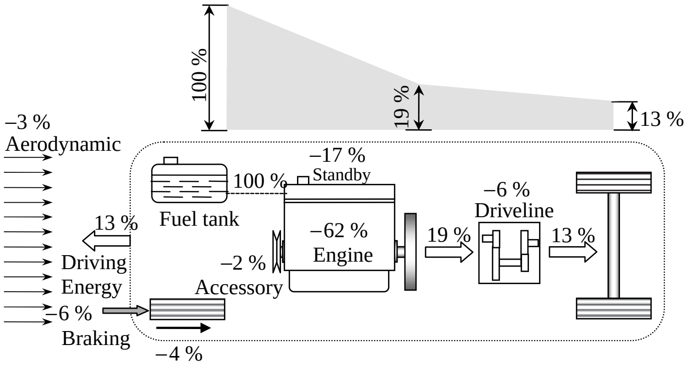
According to a review paper in 1936 by the pioneering automobile engineer, Olley [7], the typical American car of that period weighed around 2 tons (2000 kg) and had an engine power of around 100 horsepower (75 kW), resulting in a typical acceleration of about 10 ft/s^2 ($\sim$3 m/s^2), a gradeability of about 11% and a top speed around 85 m.p.h. (38 m/s $\sim$ 140 km/h). The accuracy of these performance predictions gradually improved from the 1930s onwards as measurement techniques for engine performance [8], tyre rolling resistance characteristics [9] and aerodynamic drag effects [10] improved. An example to illustrate approximately where all the energy is used in vehicle longitudinal performance is shown in Figure 1.4 for typical urban and highway conditions.

In the 1970s, there was a massive shift in interest in vehicle performance to focus on fuel economy calculations. In the USA, this was prompted by the Corporate Average Fuel Economy (CAFE) regulations first enacted by Congress in 1975; these were federal regulations intended to improve the average fuel economy of cars and light trucks sold in the USA in the wake of the 1973 oil crisis. Basically, it was the sales-weighted average fuel economy of a manufacturer's range of passenger cars or light trucks, manufactured for sale in the United States. This signalled the start of a huge amount of interest around the world in both fuel economy and the linked topic of emissions – and governments became very active in legislating for the measurement and control of both these aspects of vehicle performance.

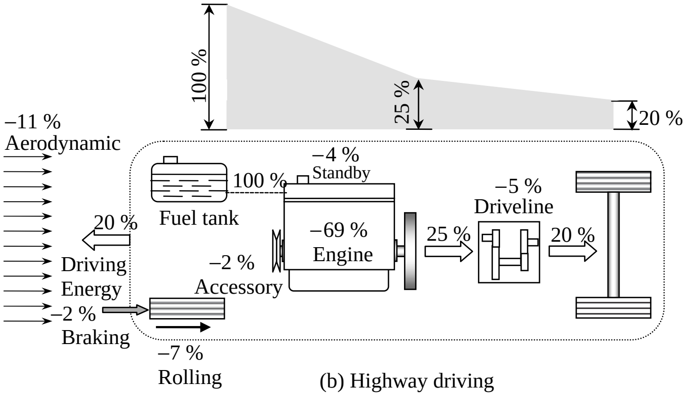
In recent decades, the highly competitive commercial environment for selling cars has meant that consumers require data and performance figures to compare different manufacturers' models. Longitudinal performance – maximum speeds, acceleration, hill climbing, towing abilities, etc. – are straightforward to measure and fairly non-controversial. In contrast, however, comparative data on fuel economy, and hence emissions – have proved extremely controversial.

The established method of quantifying a vehicle's fuel economy is to subject the vehicle, mounted on an instrumented dynamometer, to a standard drive cycle. The drive cycle simply consists of a set of data points which specify a speed vs distance travelled profile. Different drive cycles have been developed to simulate different types of vehicle operation, for example, extra-urban, urban, highway, and combined urban-highway.

Although this approach is internationally accepted, substantial detailed differences have emerged in different countries and different regions of the world. Thus, global comparisons of the fuel economy of vehicles are fraught with difficulties! Broadly speaking, the current range of standard drive cycles has emerged from the world's big three automotive markets – Europe, the USA and Asia – and the differences to some extent reflect different driving patterns in those regions. An excellent overview of the comparative



(a) Urban driving



(b) Highway driving

Figure 1.4 Example of typical energy flows during urban (a) and highway (b) driving

driving cycles is reported in [11]. The situation is further complicated by the fact that different countries or regions have developed different targets for fuel economy and emissions – which of course, makes life difficult for global manufacturers in meeting different standards for different markets.

Because of these regional differences, drive cycle testing has been a source of considerable controversy in the industry. But it has also proved extremely controversial from the consumer’s point of view, because in real-world driving it has proved virtually impossible to achieve the ideal figures obtained under the standard test conditions. To the engineering community, this is an expected outcome – the tests and measurements are carried out in laboratory conditions over a repeatable drive cycle which can only be ‘typical’ of millions of real driving conditions. The key advantage is, of course, that vehicles are at least compared under fair and repeatable conditions. Nevertheless, consumer organizations and popular car publications continue to argue that the quoted figures – which now usually have to be displayed in the vehicle windscreen while on sale – should reasonably be achievable in practice.

In the European Union, the fuel economy of passenger vehicles is commonly tested using two drive cycles, referred to as ‘urban’ and ‘extra-urban’. The urban test cycle (ECE-15) was introduced in 1999 and simulates a 4 km journey at an average speed of 18.7 km/h and a maximum speed of 50 km/h. The extra-urban cycle (EUDC) simulates a mixture of urban and highway running; it lasts 400 seconds with an average speed of 62.6 km/h and a top speed of 120 km/h. In the USA, the testing procedures are administered by the Environmental Protection Agency (EPA) and were updated in 2008 to include five separate tests – which are then weighted together to give an EPA City and Highway figure that must be quoted in car sales information. It is claimed – with some justification – that these figures are a better reflection of real-world fuel economy performance than the EU figures.

Just to add to the confusion, fuel economy continues to be quoted in different units around the world. For example, both the USA and the UK use miles per gallon (mpg) – although even these are not comparable since the US gallon is 0.83 of an imperial gallon! In Europe and Asia, fuel consumption is quoted in units of *l*/100km. Note that both lower (l) and upper case (L) can be used for litres. This is effectively an inverse of the mpg approach and a large mpg is comparable to a small *l*/100km – so, for example, 30 mpg = 9.4 *l*/100km and 50 mpg = 5.6 *l*/100km.

However, most vehicle analysts agree that overall, the drive cycles are all less aggressive than typical real-world driving; in practice, this means that they include lower values of acceleration and deceleration than typically used in normal driving situations. With the upsurge of interest in hybrid powertrains over the first two decades of 2000, there has inevitably been an enormous focus on promoting their potential fuel economy relative to conventional powertrains. This has generated an on-going debate about whether the drive cycles tend to favour HEV powertrains over conventional ICE-based powertrains. The underlying principle is that HEVs offer the biggest scope for improvement under stop-start driving conditions in heavy city traffic, for example; hence, it is argued that since most drive cycles have their bias towards urban operation and inclusion of idle periods, they can distort the potential benefits available from hybrid powertrains – but again, there are a wide range of views!

In relation to emissions, there are two aspects; both of them are commonly referred to as ‘tailpipe emissions’ for the rather obvious reason that they emerge from the exhaust pipe as products of the combustion process. The first issue is the pollutant emissions – these include carbon monoxide (CO), unburnt hydrocarbons (HC) and oxides of nitrogen (NOx). In Europe, engine emission standards were introduced in the early 1990s to reduce all these pollutants from vehicles. It led to significant improvements in harmful emissions from passenger cars. Euro 5 is due to come into effect for passenger cars in 2011 and a further tightening of the regulations, Euro 6, is planned after that for both commercial vehicles and cars.

The second issue is the carbon dioxide (CO_2) emission levels of vehicles. These have assumed increasing attention during the early part of the twenty-first century due to global concerns about the environment – and they form part of the carbon footprint calculations which have now become embedded in all aspects of life. In the UK from 2001, the vehicle tax was linked to the CO_2 emissions of new vehicle, so that vehicle emitting less than 100g/km were actually free of road tax. And in 2008, an ambitious piece of legislation was passed which committed European car manufacturers to cut average CO_2 emissions from new cars to 130g/km by 2015.

1.4 Driver Behaviour

Although the focus of this textbook is entirely on the vehicle and the engineering of its powertrain system, it is important to recognize that whenever a vehicle is used on the road, the complete system actually involves both the vehicle and its driver. The complete system is shown in Figure 1.5, in which the driver effectively acts as a feedback controller – monitoring the performance of the vehicle and feeding back this information to compare with his demand signals to the accelerator, brake, gear selection, etc. Thus, from a dynamics point of view, we are in practice dealing with a control system. In designing the vehicle engineering system, therefore, we must be aware of the driver preferences as a controller.

In subjective terms, drivers tend to prefer systems which are:

- responsive
- controllable
- repeatable
- stable