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Giancarlo Genta
Lorenzo Morello

The Automotive Chassis

Volume 1: Components Design

 Springer

The Automotive Chassis

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Giancarlo Genta • Lorenzo Morello

The Automotive Chassis

Vol. 1: Components Design

 Springer

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ABOUT THE AUTHORS

Giancarlo Genta

Giancarlo Genta received degrees in aeronautical engineering (1970) and aerospace engineering (1971) at the Politecnico of Turin. He immediately began his career at the Politecnico as Assistant of Machine Design and Technologies.

Dr. Genta has been Visiting Professor of Astronautical Propulsion Systems since 1976 and of Vehicle Mechanics since 1977 and, more recently, of Vehicle System Design in the school of Mechanical Engineering and Automotive Engineering.

He was appointed Associate Professor of Aeronautical Engines Design in 1983, at the Aerospace Engineering School of the Politecnico of Turin, becoming full professor of the same course in 1990.

He was elected Director of the Mechanical Engineering Department of the Politecnico from 1989 to 1995. He has been teaching the course of Applied Stress Analysis II for the Master of Science of the University of Illinois at the Politecnico of Turin.

He has also taught many courses in Italy and abroad as part of development cooperation projects in Kenya (two years), Somalia (six months), India (one month) and at the Bureau International du Travail (Italy).

Dr. Genta has been honorary member of the Academy of Sciences of Turin since 1996, and of the International Academy of Astronautics since 1999; he was elected full member of the same Academy in 2006.

He has coordinated the Research Doctorate in Mechatronics, since 1997.

His research activities, primarily in the field of Machine Design, have focused on static and dynamic structural analysis.

He has studied the magnetic suspension of rotating parts, vehicle dynamics and related control systems, and was one of the promoters of the Interdepartmental Laboratory on Mechatronics, where he performs research activities on magnetic bearings, moving robots and vehicle mechanics.

Dr. Genta is author of more than 270 scientific publications, covering many aspects of mechanical design, published by Italian, English and American magazines or presented in Congresses.

He has written text books on Vehicle Mechanics (published in Italian and English), adopted as a reference in some Italian and American universities. He has also written monographs on composite material design, on the storage of energy in flywheels (published in English and translated in Russian), on Rotating Systems Dynamics and popular books on space exploration.

Lorenzo Morello

Lorenzo Morello received his degree in Mechanical Automotive Engineering in 1968 at the Politecnico of Turin.

He immediately began his career at the Politecnico as Assistant of Machine Design and Technologies.

Leaving the Politecnico in 1971, went to work at a branch of Fiat dedicated to vehicle studies, one that has been joined to the new Research Centre in 1976. He participates in the development of cars and experimental prototypes for the ESV US Program. He has also developed mathematical models for vehicle suspensions and road holding simulations.

Since 1973 he has been involved in a major project for the development of mathematical models of the vehicle, to address the product policies of the company in facing the first energy crisis; as part of this activity he began the development of a new automatic transmission for reduced fuel consumption and a small direct injection diesel engine to be used on automobiles.

Dr. Morello was appointed manager of the chassis department of the Vehicle Research Unit and has coordinated the development of many research prototypes, such as electric cars, off-road vehicle, trucks and buses.

He was appointed manager of the same Research Unit in 1977 and has been leading a group of about 100 design engineers, dedicated to the development of prototypes. A new urban bus with unitized thin steel sheet body, with spot welded joints, a commercial vehicle that will start production later, a small lightweight urban car, under contract from the National Research Council, and a hybrid car, under contract from the US Department of Energy, were developed in this period of time.

He took responsibility of the Engine Research Unit in 1980; this group, of about 200 people, was primarily dedicated to the development of new car engines. He has managed the development of many petrol engines according to the principle of high turbulence fast combustion. A direct injection diesel engine for cars, many turbocharged pre-chamber diesel engines, a modular two cylinder car engine and many other modified prototypes.

He was appointed Director of Product Development in 1983; this position includes all applied research activities on Vehicle Products of Fiat Group. The Division included about 400 people, addressed to power train, chassis and bodies studies as well as prototype construction.

Dr. Morello joined Fiat Auto in 1983, to take responsibility for the development of new automotive petrol engines and the direct injection diesel (the first in the world for automobile applications). He was appointed Director for Powertrain Engineering in 1987; the objective of this group was to develop all engines produced by Fiat Auto brands. The most important activity in this period was the development of the new engine family to be produced in Pratola Serra, which included more than 20 different engines.

At the end of his career, he returned to vehicle development in 1994, as director for Vehicle Engineering; this group was addressed to designing and testing bodies, chassis components, electric and electronic systems, wind tunnels, safety center and other facilities.

Dr. Morello retired in 1999 and started a new activity as consultant to the strategic planning of Elasis, a new company in the Fiat Group, entirely dedicated to vehicle applied research.

Along with Fiat Research Center he participated in the planning of courses for the new Faculty on Automotive Engineering of the Politecnico of Turin, and prepared related lecture notes.

He was contract professor of Vehicle System Design and has been contract professor of Automotive Transmission Design for many years at the Politecnico of Turin and the University of Naples; he also published a textbook on this last subject and many articles about the evolution of car technology.

FOREWORD

These two books on the chassis are part of a series sponsored by ATA (the Italian automotive engineers association) on the subject of automotive engineering; they follow the first book, published in 2005, on automotive transmission.

This event, which I hope will be repeated in the future, is the result of a significant effort lasting more than five years and not yet accomplished.

The Fiat Group is, in fact, well aware of the importance of specialized knowledge on the development and management of a highly competitive product and has turned to the Politecnico of Turin for the opportunity of setting up a course on automotive engineering, addressed to first and second level degree achievement, for specialists who will be dedicated to the development, production and continuous improvement of automotive products.

This course was aimed not only to provide new resources for the company, but also to sustain the company itself in the globalization process, only possible with a cultural homogeneity between parts or services suppliers and people in charge of delocated processes.

This course, operative in Turin since the academic year 1999/2000, has been planned and begun as a result of a project that involved Professors of the Politecnico, addressed to the automotive disciplines and experts of many companies of the Fiat Group; the participation of these experts was not limited to the planning of specialist courses, but was also extended to the preparation of lecture notes and, quite often, to actual teaching activity.

Fiat assigned this task to the Fiat Research Center, for many reasons.

Fiat Research Center (CRF) has the responsibility not only for designing innovative products, but also for developing new processes for product development and production. In addition, CRF must diffuse and make available to the

company's operating sectors the knowledge that derives from new product development, to assure a quick introduction of competitive products to the market.

Finally, CRF is dedicated not only to automobiles, but also to other automotive products and components and to production systems; for this reason it has been possible to include industrial vehicles and component suppliers, taking for granted a greater emphasis on automobiles.

This task was particularly difficult and involved the participation of many specialists of the Research Center and a number of experts from the operating field; the result of this effort consists not only in an integrated studies plan, but also complete lecture notes and audiovisual aids to support lessons and the activities of students.

The quantity of this material has encouraged us to go further, with the intention of transforming this material into reference books in Italian and, possibly, in the English language.

The Automotive Chassis is dedicated to the design of related components and their integration into the vehicle, in order to obtain customer satisfaction. This book supports the courses of Automotive System Design, Automotive Chassis Design and Automotive Transmission Design that are held at the Politecnico of Turin as part of the Automotive Engineering Course.

ATA, our Italian associations of automotive engineers, has overseen publication of the Italian edition; this task fits well with the institutional objectives of the association, to diffuse and foster automotive culture among young people.

Nevio Di Giusto
CRF and Elasis Chief Executive Officer

PREFACE

This book is the result of two decades of experience: From one side the experience of teaching courses such as Vehicle Mechanics, Vehicle System Design, Chassis Design and more to students of Engineering; from the other the design praxis of vehicle and chassis components in a large automotive company. This book is addressed primarily to students of automotive engineering and secondarily to all technicians and designers working in this field. It is also addressed to all enthusiasts who are looking for a technical guide.

The tradition and the diversity of disciplines involved in road vehicle design lead us to divide the vehicle into three main subsystems: The engine, the body and the chassis.

The chassis is no longer – as engine and body are – a visible subsystem created in a certain part of the fabrication process; chassis components are assembled, as a matter of fact, directly on the body. For this reason the function of the chassis cannot be assessed separately from the rest of the car.

As we will see better when reading the chapters in this book dedicated to historical evolution, the situation was completely different in the past; in the first cars the *chassis* was defined as a real self-moving subassembly, one that included:

- A structure, usually a ladder *framework*, able to carry on all the remaining components of the vehicle.
- The *suspensions* for the mechanical linkage of wheels with the framework.
- The *wheels* and their tires.

- The *steering system* for changing wheel angles according to vehicle path.
- The *brake system* for reducing speed or stopping the vehicle.
- The *transmission* for applying engine torque to the driving wheels.

This group of components, after engine assembly, was able to move autonomously, as occurred in many experimental tests, where the body was simulated with a ballast and the chassis moved during the fabrication process from the shop of the car maker to that of the body maker.

Customers often bought a chassis from the car maker to be completed later by a body maker, according to their desire and specification.

In contemporary vehicles this particular architecture and function is only available for industrial vehicles, with the exception of buses where the structure, even if built by a body maker, contributes along with the chassis framework to the total stiffness, forming a kind of unitized body.

In almost every car the chassis structure cannot be separated from the body, being part of its floor (*platform*); sometimes an auxiliary framework is also added to interface the suspension or power train to the body, enabling their pre-assembly at the side of the main assembly line.

Nevertheless tradition and particular technical aspects of these components have justified the development of a particular discipline within vehicle engineering; as a consequence almost all car manufacturers have a technical organization addressed to the chassis, separated from those addressed to body or engine.

Another reason has been added in recent times to justify a different discipline and a specific organization. This is the creation of the so called *technological platforms*: The modern trend of the market calls for an unprecedented product diversification, of a sort never attained in the past; marketing experts sometimes call this phenomenon fragmentation.

This high degree of diversification could not be sustained with acceptable production costs without a strong cross standardization of non-visible or non-specific parts of certain models.

This situation has been well known to all industrial vehicle manufacturers for years. The term ‘platform’, implying the underbody and front side members, with the addition of the adjective ‘technological’, describes a set of components substantially equal to the former chassis. The particular technical and scientific issues, the different development cycle, the longer economic life have reinforced the specificity of engineers dedicated to this car subsystem.

The contents of this book are divided into five parts, organized into two volumes.

The first volume describes primary chassis subsystems in two parts.

The first part describes the primary components of the chassis from the tire to the chassis structure, including wheels, suspension, steering and braking systems, not forgetting the control systems now becoming increasingly important because of the diffusion of active and automatic systems.

The second part is addressed to the transmission and related components; the complexity of this topic justifies a separate presentation.

It should be noticed that, among many car manufacturers, the engineering and production organizations dedicated to this subsystem are integrated into the power train organization, instead of the chassis organization. This has obviously no influence on the technical contents of this book and can be justified by standardization issues and the life cycle of this component, in certain respects more like to the engine than the chassis.

The explanation of chassis components assumes the existence of a general knowledge of mechanical components, which can be gathered through a conventional machine design course. Topics that can be found in a non-specific course are not treated. In the second part in particular gear design will not be approached exhaustively, nor will shaft, bearing and seal design.

Nevertheless, in many parts of this book design and testing information not usually approached in general purpose design courses is introduced and discussed.

We also decided to spend two chapters on the historical evolution of the automotive product; those should enable the reader to appreciate the technical progress of the car in its first hundred years of life. In the opinion of the authors, this subject is useful as technical training and is sometimes inspirational as well.

Only architectures that are typical of the most widely used road vehicles will be considered: cars, with some mention of industrial vehicles. We will not consider other applications, such as motor bicycles, tractors or earth-moving machines and quadricycles.

The second volume is divided into three parts and is entirely addressed to the chassis as a system, considering the contribution of the chassis to vehicle performance, as perceived by the customer and imposed by legislative rules.

The third part is dedicated to an outline of the functions that the vehicle is expected to perform, of customer expectations and pertinent legislation.

In the fourth part the influence of chassis design on vehicle performance is explained. In particular, the longitudinal, transversal and vertical dynamics is explained, along with its influence on speed, acceleration, consumption, braking capacity and maneuverability (or handling) and comfort.

The fifth part is addressed to mathematical models of the chassis and at large vehicle. Automotive engineers take more and more advantage of mathematical models of virtual prototypes and perform numerical testing before the prototypes are available for physical tests.

Even if mathematical models are based upon calculation codes that are prepared by specialists and are available on the market, we think it necessary to supply students with a clear idea of the methods behind these codes and the approximations these codes imply. The purpose of this section is not to enable specialists to built up their models, but to suggest a correct and responsible usage of their results.

The two books are completed by five appendices.

The first appendix reviews basic system dynamics, useful for understanding the creation of the mathematical models that are introduced in the fourth and fifth part.

The second appendix is dedicated to two wheel vehicles. The study of two wheel vehicles, in some respects more complicate than four wheel vehicles, is very particular and has nothing to do with cars. In addition, industries that produce motorcycles are in a different category from the car industry.

Nevertheless, there are disciplines common to the two worlds, due to the fact that both vehicles use pneumatic tires as their interface with the ground; knowledge exchange between vehicle engineers in both camps could be of mutual benefit.

The third appendix is dedicated to the particular issues that must be faced when vehicles on wheels will be developed for planets or environments different from the earth. Beginning with the only vehicle of this kind that was developed for the Apollo Project, similarities and differences between conventional vehicles and those that in the future could be utilized for interplanetary exploration will be discussed.

The fourth appendix analyzes various mathematical approaches, sometimes simplified, to interpret the motion of cars after the impact due to an accident.

The last appendix reports the primary data of vehicles of different kinds that are used in explanatory examples in the book; these data also enable students to practice their skills on exercises with a minimum of realism.

Torino, Italy

Giancarlo Genta
Lorenzo Morello

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The authors are also indebted with their editors: Paul Gilster deeply revised the English text; Natalie Jacobs put the finishing touches on the book.

The first volume of this work has, in addition, benefited from the lecture notes prepared by Fiat Research Center to sustain the teaching activity of the courses of Vehicle System Design, Chassis Design and Automotive Transmission Design, within the course of Automotive Engineering of the Politecnico of Turin and of the Master in Automotive Engineering of the Federico II University of Naples.

The authors' gratitude must also be shown to the companies that supplied part of the material used for the illustrations, mainly in the first volume; in alphabetical order we remember: Audi, Fiat Auto, Getrag, Honda, Iveco, Marelli, Mercedes and Valeo. Without their contribution this book would be neither complete nor topical.

LIST OF SYMBOLS

a	acceleration; generic distance; distance between center of gravity and front axle
b	generic distance; distance between center of gravity and rear axle
c	viscous damping coefficient; specific heat
d	generic distance, diameter
e	base of natural logarithms
f	rolling coefficient; friction coefficient
f_0	rolling coefficient at zero speed
\mathbf{f}	force vector
g	gravity acceleration
h	wheel deflection
h_G	center of gravity height on the ground
k	stiffness
l	wheelbase; length
m	mass
p	pressure
r	radius
s	stopping distance, thickness
t	temperature; time; track
\mathbf{u}	displacement vector
v	slipping speed
z	number of teeth
A	area
C	cornering stiffness; damping coefficient
C_γ	camber stiffness

C_0	cohesiveness
E	energy; Young modulus
F	force
G	shear modulus
H	thermal convection coefficient
I	area moment of inertia
J	quadratic mass moment
K	rolling resistance coefficient; stiffness; thermal conductivity
K	stiffness matrix
M	moment
M_f	braking moment
M_m	engine moment
M_z	self-aligning moment
P	power; tire vertical stiffness; force
P_d	power at the wheel
P_m	power at the engine
P_n	required power
Q	thermal flux
R	undeformed wheel radius; path radius
R_e	rolling radius
R_l	loaded radius
S	surface
T	temperature, force
V	speed; volume
W	weight
α	sideslip angle; road side inclination; angle
α_t	road transverse inclination angle
γ	camber angle
δ	steering angle
ϵ	toe-in, -out; brake efficiency; deformation
η	efficiency
θ	angle; pitch angle
μ	torque transmission ratio; adherence coefficient
μ_p	maximum friction coefficient
μ_x	longitudinal friction coefficient
μ_{x_p}	max longitudinal friction coefficient
μ_{x_s}	slip longitudinal friction coefficient
μ_y	transversal friction coefficient
μ_{y_p}	max transversal friction coefficient
μ_{y_s}	slip transversal friction coefficient
ν	speed transmission ratio; kynematic viscosity
ρ	density
σ	normal pressure; slip
τ	transversal pressure; transmission ratio

ϕ	angle; roll angle, friction angle
ω	pulsation; frequency
Φ	diameter
Π	tire torsion stiffness
χ	torsion stiffness
Ω	angular speed

INTRODUCTION TO PART I

The first part of this book is dedicated to the study of the often complex subsystems (such as suspensions) that constitute the chassis. Their primary function is to mediate the exchange of force with the ground, thus obtaining the desired vehicle speed and path.

With reference to the system of coordinates that will be defined in part four, the forces exchanged with the ground can be classified as:

- Forces perpendicular to the ground (vertical for the motion on a plane road); in steady state conditions these forces can be considered constant, but because of obstacles on the road, they are variable; they are a factor in passenger comfort.
- Longitudinal forces; these are primarily due to propulsion (engine and transmission) and braking systems; they are relevant to vehicle speed control.
- Transversal forces; these are due to wheel steering angles, and they are relevant to road holding and stability.

All these forces act on tires that because of their deformable structure, make the dynamic behavior of the vehicle more like a floating or flying vehicle than a rail vehicle.

Although chassis technologies can be defined as mature, we should not underestimate the ongoing evolution of controlled or active systems based upon electronic and informatic technologies.

In fact the rapid development of automotive electronics, in terms of performance and cost has had and will continue to have a big influence on improving the active safety and comfort of vehicles.

Nor it should be forgotten that in many markets the development and production of chassis systems is being outsourced by car manufacturers to parts manufacturers, who are becoming specialists in their business.

This has been true for many years of brake systems, steering systems and tires; it is now becoming true for suspensions. Given this situation, it is important for those who will address their career to car or parts manufacturing to develop a good understanding of these systems; the development of these components is virtually impossible if separated from that of the vehicle.

As we will see, chassis components have evolved quickly in recent years: today almost all cars feature radial tires with low aspect ratios (the radial dimension is much smaller than transverse dimension) and need suspensions with precise elasto-kinematic behavior. Mc Pherson and double wishbone suspensions share the market as far as front axles are concerned, while a significant percentage of rear axles feature multilink suspensions.

It is unlikely that the kinematic configuration will see new innovations; the same can be said for the steering system, where the wide diffusion of power systems has almost standardized the rack and pinion configuration.

A similar situation can be seen for car brake systems, where disc brakes are widely diffused with the exception of the rear axle of economy cars that preserve the drum solution.

New developments are, however, expected for electronic control systems and the related fields of sensors and actuators, where electromechanical actuators offer more opportunities for performance improvements.

Electronic control systems have initially entered the market as add-on devices.

The case of the brake antilock system (ABS) is typical: It made significant performance improvements to the brake system at the cost of new and sophisticated components (the electronic control system, wheel speed sensors, a valve group able to regulate the pressure on the brake actuators of the wheel independent of the pedal pressure).

Although the introduction of this system was gradual, it later reached high volumes with consistent cost reduction and now, as a consequence, its diffusion is nearly total. At the same time system performance was improved, offering new possibilities, either in terms of cost reduction (i.e. offering the possibility of incorporating the brake distribution valve function at no cost), or in terms of functions where, with the addition of various sensors vehicle dynamic control has been obtained.

A similar story can be told for power steering systems, initially totally hydraulic; the addition of electronic controls allowed better regulation of the power assistance pressure, reducing the sensitivity of the steering wheel torque to the vehicle speed.

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