

Ground Vehicle Engineering Series

Driveline Systems of Ground Vehicles

Theory and Design



**Alexandr F. Andreev
Viachaslau I. Kabanau
Vladimir V. Vantsevich**

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Contents

Series Preface	xiii
Preface	xv
Acknowledgments	xxi
Authors	xxiii
List of Symbols	xxv
1. Driveline Systems and Vehicle Performance.....	1
1.1 Brief Review of Driveline Systems History	1
1.1.1 First Wheeled Carriages.....	1
1.1.2 First Differential Transmissions	4
1.1.3 First Hybrid Cars and All-Wheel Drive Vehicles.....	7
1.1.4 Front-Wheel Drive Designs	7
1.1.5 First Mechanical Four-Wheel Drives.....	8
1.1.6 Invention of Pneumatic Tires and Design Measures for Improving the Poor-Terrain Mobility of Vehicles.....	9
1.1.7 Constant-Velocity Joints.....	12
1.1.8 All-Wheel and Multiwheel Drive Trucks and Passenger Cars	14
1.1.9 Power Dividing Units.....	28
1.2 Classification of Driveline Systems and Power Dividing Units.....	33
1.3 Wheel Dynamics and Energy Efficiency.....	56
1.3.1 Five Power-Loading Modes	56
1.3.2 Kinematic and Force Factors	61
1.3.2.1 Effective Rolling Radius and Slip Ratio	61
1.3.2.2 Wheel Force and Torque Factors	66
1.3.3 Wheel Power and Force Balance	70
1.3.4 Motion with a Slip Angle	75
1.3.4.1 Interaction between Longitudinal and Lateral Forces	75
1.3.4.2 Wheel Kinematic and Force Factors under Sideslip	77
1.4 Vehicle Energy/Fuel Efficiency and Driveline Systems Design.....	80
1.4.1 Mechanical Power Losses in Driveline Systems.....	82
1.4.2 Mechanical Power Losses in Wheel Systems.....	86
1.4.2.1 Tractive Operating Mode	86
1.4.2.2 Transportation Operating Mode	90
1.4.2.3 Combined Operating Mode.....	94
1.4.3 Fuel Efficiency of Multiwheel Drive Vehicles.....	96
1.5 Vehicle Performance and Driveline Systems Design.....	101
1.5.1 Traction and Velocity Properties of Vehicles.....	103
1.5.2 Mobility of Vehicles.....	106
1.5.3 Turnability.....	107
1.5.4 Stability of Motion	110
1.5.5 Handling of the Vehicle	112
1.6 Principles of Driveline System Design.....	114

2. Interwheel and Interaxle Open and Lockable Differentials.....	119
2.1 Kinematics and Dynamics of Differentials:	
The Gear-Ratio Concept.....	119
2.2 Kinematics of a Vehicle with an Interaxle Differential.....	132
2.2.1 Vehicle with Front-Steered Wheels.....	132
2.2.2 Vehicle with Front- and Rear-Steered Wheels.....	137
2.3 Tooth Forces in Bevel-Gear Differentials.....	139
2.3.1 Axial Forces in a Pinion-Side Gear Mesh.....	139
2.3.2 Total Axial Forces in Bevel Differentials.....	146
2.3.3 Force Evaluation: A Method for Practical Use.....	153
2.3.4 Experimental Results.....	157
2.3.5 Conclusion.....	159
2.4 Robustness of Differentials.....	161
2.5 Design of Axle/Interwheel Differentials.....	168
2.5.1 General Engineering Issues and Solutions.....	168
2.5.2 Design of Differential Geometry.....	185
2.5.2.1 Highway Heavy-Duty Trucks.....	189
2.5.2.2 Articulated Timber Carriers.....	191
2.5.2.3 Farm Tractors.....	195
2.5.3 Oil Lubrication Systems.....	202
2.6 Design of Interaxle Differentials and Transfer Cases.....	209
2.6.1 General Engineering Issues and Solutions.....	209
2.6.2 Design of Differential Geometry.....	219
2.6.3 Oil Lubrication Systems.....	227
2.6.3.1 Lubrication Systems for Interaxle Differentials of Driving Tandems.....	227
2.6.3.2 Lubrication Systems for Transfer Cases.....	233
2.7 Designing Locking Devices.....	238
2.8 Wheel Power Distribution and Vehicle Performance.....	249
2.8.1 Generalized Vehicle Parameters and Energy/Fuel Efficiency.....	249
2.8.2 Vehicle Tractive and Velocity Properties.....	264
2.8.3 Vehicle Turnability and Stability of Motion.....	268
2.9 Optimal and Reasonable Differential Gear Ratios: Control Principles.....	274
3. Automatic and Manual Positively Engaged Power-Dividing Units.....	289
3.1 Designs of Power-Dividing Units.....	289
3.2 Kinematic Discrepancy and Generalized Vehicle Parameters.....	301
3.2.1 Vehicles with 4×4 Wheel Formula.....	301
3.2.2 Vehicles with $2m \times 2n$ Wheel Formula.....	305
3.2.2.1 Vehicles with $2m \times 2n$ Wheel Formula in Rectilinear Motion.....	306
3.2.2.2 Vehicles with $2m \times 2n$ Wheel Formula with Steered Wheels in Curvilinear Motion.....	309
3.2.2.3 Articulated $2m \times 2n$ Vehicles with Steered Wheels.....	312
3.2.2.4 The Interwheel Positive Engagement.....	317
3.3 Wheel Slips and Circumferential Wheel Forces.....	318
3.3.1 4×4 Vehicles.....	319
3.3.2 $2m \times 2n$ Vehicles.....	326

3.4	Wheel Power Distributions and Vehicle Energy/Fuel Efficiency	330
3.4.1	Mechanical Power Losses in Wheel Systems.....	330
3.4.2	Mechanical Power Losses in Driveline Systems.....	338
3.4.3	Combined Power Losses in Driveline and Wheel Systems—Fuel Consumption	343
3.5	Wheel Power Distribution and Vehicle Performance	355
3.5.1	Vehicle Tractive and Velocity Operational Properties	355
3.5.2	Vehicle Turnability and Stability of Motion	358
3.6	Optimal and Reasonable Kinematic Discrepancy: Control Principles.....	368
4.	Limited Slip Differentials	379
4.1	Torque Biasing and Locking Performance	379
4.2	Disk Differentials without Additional Lockers.....	385
4.3	Disk Differentials with Cam Lockers	391
4.4	Disk Differentials with V-Lockers	399
4.5	Worm-Gear Differentials.....	405
4.6	Cam-Plunger Differentials	413
4.7	Torque Sensitive Differentials	418
4.8	Speed Sensitive Differentials	432
4.9	Force Fluctuations in Disk Differentials	435
4.10	Tractive Performance and Yaw Moment of a Drive Axle	443
4.11	Asymmetrical Interaxle Differentials.....	448
5.	Free-Running Differentials and Viscous Clutches	453
5.1	Design and Operating Principles of Free-Running Differentials	453
5.2	Applications of Free-Running Differentials	463
5.3	Viscous Clutches: Operation and Design Aspects	466
6.	Combined Automated Mechanical Driveline Systems.....	475
6.1	Vehicle Operational Properties	475
6.1.1	Vehicles with Steered Wheels	475
6.1.2	Articulated Vehicles with Steered Wheels	486
6.2	A Method of Synthesizing Driveline Systems with Optimal Properties.....	492
6.3	Objective Function Analysis	496
6.4	Synthesis of the Properties of Interwheel Power-Dividing Units.....	510
6.5	Synthesis of Properties of Interaxle Power-Dividing Units	519
6.6	Synthesis of Properties of Interwheel and Interaxle Power-Dividing Units	531
6.6.1	The Mathematical Model of a Vehicle	531
6.6.2	Optimal Properties.....	539
7.	Mechatronic Driveline Systems.....	555
7.1	Simple, Combined, and Integrated Driveline Systems—A Brief Overview	555
7.2	Inverse Wheel Dynamics and Control.....	560
7.3	Proactive Assessment of Terrain Conditions	568
7.4	Kinematics and Dynamics of Mechanical Subsystems.....	574

7.4.1	The Open Differential.....	577
7.4.2	Double Differentials.....	580
7.4.3	The Open Differential with Three-Link Planetary Rows.....	587
7.4.4	Single-Row Planetary Mechanism with Mating Pinions.....	591
7.5	Design of Simple and Combined Driveline Systems.....	596
7.6	Design of Integrated Driveline Systems.....	605
7.6.1	Optimal Power Distribution and Features of the System.....	606
7.6.2	Synthesis and Implementation of a Parallel Control Algorithm.....	620
7.6.2.1	Logical Control Languages.....	620
7.6.2.2	The Logical Control Algorithm.....	621
7.7	Hybrid Driveline Systems.....	626
7.7.1	Advanced Hybrid-Hydraulic Driveline Systems.....	626
7.7.2	Design Selection of the Kind and Standard Dimension of Hydraulic Units.....	639
8.	Testing of Driveline Systems and Multiwheel Drive Vehicles.....	649
8.1	Laboratory Studies of the Locking Performance of Differentials.....	649
8.2	Laboratory Testing of Friction Clutches of Differentials.....	662
8.3	Laboratory Tests of Differential Lubrication Systems.....	667
8.4	4 × 4 Vehicle Chassis Dynamometer with Individual Roll Control.....	679
8.5	Field and Road Tests of Wheeled Vehicles.....	690
Problems and Questions.....		711
Bibliography.....		729
Index.....		743

Preface

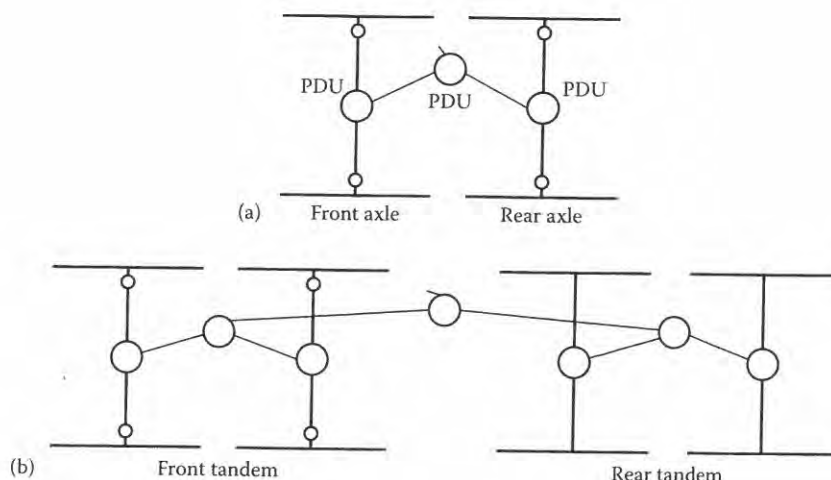
The dynamics and performance of a vehicle manifest themselves in the interaction of the vehicle with the surroundings and result from its properties such as energy/fuel efficiency, terrain mobility, tractive and velocity properties, vehicle turnability, stability of motion and handling, braking properties, and smoothness of ride. A distinctive feature in the design of vehicles with four or more driving wheels that is of great significance is that many of their properties depend markedly not only on the total power applied to all the driving wheels but also on the distribution of the total power among the wheels. Under given road or terrain conditions, the same vehicle with a constant total power at all the driving wheels, but with different power distributions among the driving axles and the left and right wheels of each axle, will perform differently; that is, the criteria of the above-mentioned vehicle properties will have different quantitative values. In practical engineering terms, this means that due to different power distributions among the driving wheels, a given vehicle will demonstrate variable fuel consumption, terrain mobility, and traction, and will accelerate differently and turn at different radii. Depending on the wheel power split, the vehicle can "unexpectedly" run into either understeering or oversteering and can sometimes become unstable, skidding in a lateral direction and eventually rolling over.

The power distribution among the driving wheels is largely determined by the vehicle's driveline system, which is generally defined as a part of the power train, located between the transmission and the driving wheels. A driveline system includes a set of mechanisms and subsystems which have been referred to in this book as power-dividing units (PDUs). Typically, a PDU has one input and two outputs. These units are employed in transfer cases, interaxle reduction gears, and driving axles. For a vehicle with one engine and with a conventional axle-type driveline system layout (which differs from the left-right side layout), the number of PDUs is equal to the number of the driving wheels less one. For example, a vehicle with four driving wheels will have three PDUs and a vehicle with eight driving wheels will have seven PDUs (see Figure 1).

It should be obvious to the reader that the number of combinations of mechanisms and subsystems that can be employed even in three PDUs of a vehicle with two driving axles is virtually limitless. In fact, a list of such mechanisms and subsystems may be compiled of open differentials and positively locked units, limited slip differentials with all kinds of torque biases, mechanically and electronically locked differentials, viscous couplings, NoSPINs, and also most current developments that are commonly referred to as torque-vectoring or torque-management systems.

This gives rise to two fundamental engineering problems: First, how to investigate the effect of different driveline systems on the properties of vehicles, their dynamics, and performance? Second, how to determine the optimal characteristics of the driveline system and its PDUs and then design them for a specific vehicle in a manner that would ensure a high level of dynamics and performance, mobility and fuel efficiency, traction and acceleration, and stability of motion and turnability?

Probably the first study of the effect of a driveline system on vehicle motion was the research paper of Prof. Nikolay E. Zhukovskiy, titled "The theory of the instrument of engineer Romeyko-Gurko," published in 1903. The developments in the theory, design, and manufacture of vehicles with four or more driving wheels—all-wheel drive and multiwheel drive vehicles (see Section 1.2)—were to a large extent facilitated by

**FIGURE 1**

Driveline system layouts of (a) 4×4 and (b) 8×8 vehicles.

experience gathered during World War II: The shortage of arterial and high-type roads and the poor terrain mobility of vehicles determined how military applications progressed for many postwar years. After World War II, with the development of hard-surface roads, multiwheel drive vehicle layouts were actively designed and employed in the agriculture sector, and in construction, forestry, and the petroleum industry. At a later stage when space research and space flights began, planet rovers were also designed with all the wheels driven by torque. From the 1980s onward, passenger cars and sport-utility vehicles with four driving wheels became very popular. The twentieth century thus saw the emergence of multiwheel-drive vehicles of all types. In conjunction with this, the names of many engineers, researchers, and professors, who developed the theory of motion of vehicles and the practice of driveline system design, should be mentioned here. This is a very difficult task and I fully realize that I could fail to mention many of them. However, the following persons deserve special mention: Yakov S. Ageykin, Alexander S. Antonov, Dmitriy A. Antonov, Pavel V. Aksenov, Mieczyslaw G. Bekker, Nikolay F. Bocharov, G. Brouhiet, Colin Chapman, Evgeniy A. Chudakov, Keith Duckworth, J. R. Ellis, Yaroslav E. Farobin, Thomas G. Gillespie, Wunibald Kamm, Frederick W. Lanchester, Andrey S. Litvinov, William F. Milliken and Douglas L. Milliken, M. Mitschke, Tatsuro Muro, Maurice Olley, Hans B. Pacejka, Vladimir A. Petrushov, Yuliy V. Pirkovskiy, Vladimir F. Platonov, A.R. Reece, Robin Sharp, Anatoliy T. Skoybeda, Gleb A. Smirnov, Sergei B. Shukhman, Jaroslav J. Taborek, Igor S. Tsitovich, Jo Y. Wong, and Georgiy V. Zimelev.

Engineering designers and their design developments are now part of history; notable engineers among them include N.A. Astrov, Marius Berliet, William Besserdich, Carl Borgward, Henry Bussing, Carlo Cavalli, John W. Christie, V.E. Chvyalev, Wesley M. Dick, G.A. Fest, V.A. Grachev, Nikolay I. Korotonoshko, A.M. Kriger, I.P. Ksenevich, Nils Magnus, Alfred Masury, A.A. Lipgart, Ralf Nash, Ferdinand Porsche, Wilfredo Ricart, Delmar B. Roos, B.L. Shaposhnik, and M.S. Vysotskij. Vitali A. Grachev, chief design engineer, who has designed many forms of multiwheel drive vehicles, became legendary in the former U.S.S.R. among experts who designed military vehicles. Boris L. Shaposhnik established the Special Design Office, known by its Russian-language acronym, SKB-1, in Minsk, Belarus, where new-generation vehicles, such as multiwheel drive missile carriers,

were designed. Vladimir E. Chvyalev followed in the footsteps of B.L. Shaposhnik. He headed the design department of the Minsk Wheeled Tractors Company that grew out of SKB-1. Dr. Mikhail S. Vysotskij, academician at the National Academy of Sciences of Belarus and chief design engineer of automotive vehicles in Belarus led the design of heavy-duty vehicular trains. Even now, in spite of advancing years, he directs a scientific research institute of the National Academy of Sciences.

Another eminent individual in the field, Professor Anatoliy Kh. Lefarov, a design engineer, subsequently became a professor of Belarusian National Technical University (the current name), Minsk, Belarus; Dr. Lefarov was the deputy of chief design engineer, V.A. Grachev, and the first deputy of chief design engineer, B.L. Shaposhnik. During the 1960s, Dr. Lefarov established a research group in the field of multiwheel drive vehicles that designed various driveline systems and PDUs and performed analytic and experimental studies on the effect of driveline systems on the properties of vehicles.

We have been associated with Dr. Lefarov's research group for our entire professional lives. Dr. Kabanau was his first postgraduate student and then became the principal design engineer, who has to his credit designed many mechanisms and systems. Dr. Andreev is concerned with simulating the motion of vehicles and designing PDUs. Seventeen professionally fortunate years, which have rapidly slipped away, with our leader united me not only in a common endeavor but also in a binding friendship. Dr. Lefarov has shaped me not only as an expert but also as a human being. It so happened that after he passed away in 1992, I became the leader of our group.

The culmination of all of this has led to this book. This book comprehensively covers the subject matter from a historic overview, classification, and the nature of driveline influence on vehicle dynamics and performance (Chapter 1), through analytical fundamentals (Chapters 2 through 5) and optimization and control of wheel power distributions (Chapters 6 and 7), to mechanical and mechatronic design of advanced systems (Chapters 2 through 7) and experimental research and tests (Chapter 8). Also, I believe the readers will thoroughly enjoy the illustrations, hand-drawn by Dr. Kabanau.

In many ways, this book is unique; it is probably the only book that deals with the solution of the two fundamental engineering problems that were formulated earlier in the preface. Therefore, the reader can see that the book presents an analytical treatment of driveline systems research, design, and tests based on vehicle dynamics and performance requirements. Methodologically, this is described in two ways. First, the book introduces analytical tools for studying the driveline effects on power distribution among the driving wheels and then on the dynamics and performance of vehicles. Engineering applications of these tools, for instance, include the comparative analysis of several driveline systems with the purpose of selecting a driveline system that provides a given vehicle with better performance and also to evaluate same-class vehicles with different driveline systems. Additionally, the developed techniques adequately supplement the mathematical modeling of vehicle dynamics. Chapters 1 through 5 and Chapter 7 present the necessary material for such mathematical modeling of driveline systems that can be compiled of different types of PDUs. All analytical techniques were built based on the so-called generalized vehicle parameters, which integrate characteristics of PDUs with tire (or combined tire/soil) characteristics and, implicitly, suspension characteristics.

Second, the book develops methodologies for the synthesis of optimal characteristics of PDUs that can be applied to different types of vehicles. Thus, a researcher would not need to run a comparative analysis of hundreds of potential driveline systems to try to find a better one for the vehicle under design. Instead, optimal characteristics can be directly achieved and then optimal PDUs can be designed. Respective analytical techniques were

based on the principles of driveline system designs that were developed on the inverse vehicle dynamics approach and first introduced in this book. To learn more about the inverse vehicle dynamics approach and the optimization of power distribution among the driving wheels, the reader should start with Sections 1.5 and 1.6, then go through Sections 2.9 and 3.6, and finally to Chapters 6 and 7. The mechanical design of PDUs and control development issues are covered in Chapters 2 through 5, and also in Chapter 7.

The book is also unique in the sense that it was written virtually entirely on the basis of the results of investigations by its authors. All analytical tools, and computational, design, and test methods were verified through many engineering projects; some of the projects are presented in this book as illustrative examples to prove the applicability of the developed theories. The material in this book will provide the reader with answers to intriguing engineering problems such as achieving higher energy/fuel efficiency of a vehicle by driving either all the wheels or not all the wheels, obtaining oversteering characteristics by increasing the torque at the front-steered wheels, and many other such technical problems. Engineering workers will find interesting methods of design and experimental studies of new driveline systems that provide for optimal/specified vehicle properties. The presented methodologies and results on the optimization of wheel power distributions among the driving wheels can also be of interest to engineers working on vehicles with individual wheel drives and vehicles with hybrid driveline systems.

The reader will find only some of the references in the text to the detailed bibliography at the end of the book. The bibliography reflects that, to a large degree, the history of investigations in driveline system engineering and vehicle dynamics during the twentieth century and the start of the twenty-first century was compiled by studying a large number of publications and it should be regarded as a source of additional engineering data; after all, the experience of each expert is unique. We have conscientiously investigated publications on the theory of motion of all-wheel-drive vehicles and on driveline system design for many years and, if we missed some important investigations and did not include them in the bibliography, we apologize to the authors. We have also included some of our own publications in the bibliography that reflect not only the results of investigations but also, by representing a sequence, give an idea about the development of our scientific and engineering approaches to, and methods of, solutions for engineering problems.

The volume of the scientific and engineering information and the structure of its arrangement within the book are such that it could be used both by beginning design and test engineers as well as engineers with experience in the design and experimental studies of various PDUs, driveline systems, and multiwheel drive ground vehicles as a whole. The book will also be useful to research engineers involved in simulating motion and in testing multiwheel drive vehicles, because it illuminates many aspects of the mathematical simulation of the different driveline systems and dynamics of such vehicles, something that is usually not examined in classical textbooks on vehicle dynamics. The simulation of vehicle dynamics on the basis of the inverse dynamics approach is also a topic that is examined in this book for the first time. This method is also used for working out algorithms for the control of mechatronic driveline systems.

For many years, we developed and delivered university-level courses on the theory of vehicle motion and on the design of driveline systems. This book was written with reference to these courses and can therefore also be used as a textbook on advanced vehicle dynamics and on the design of driveline systems in master of science and PhD courses. Thereby, all the mathematical formulae in the book have been derived together with the necessary detailed explanations, something that makes the material easily comprehensible and convenient both for the student and the lecturer. The analytical results are illustrated by

quantitative examples (illustrative problems) and examples of developing driveline systems and PDUs. Using our experience, we devised engineering problems associated with the dynamics of vehicular motion, design, and testing of driveline systems. These problems developed for each chapter can be used in the course of studies as examination problems or homework assignments, and also by practicing engineers for better familiarization with the material in the book and for illustrating its underlying theoretical principles.

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