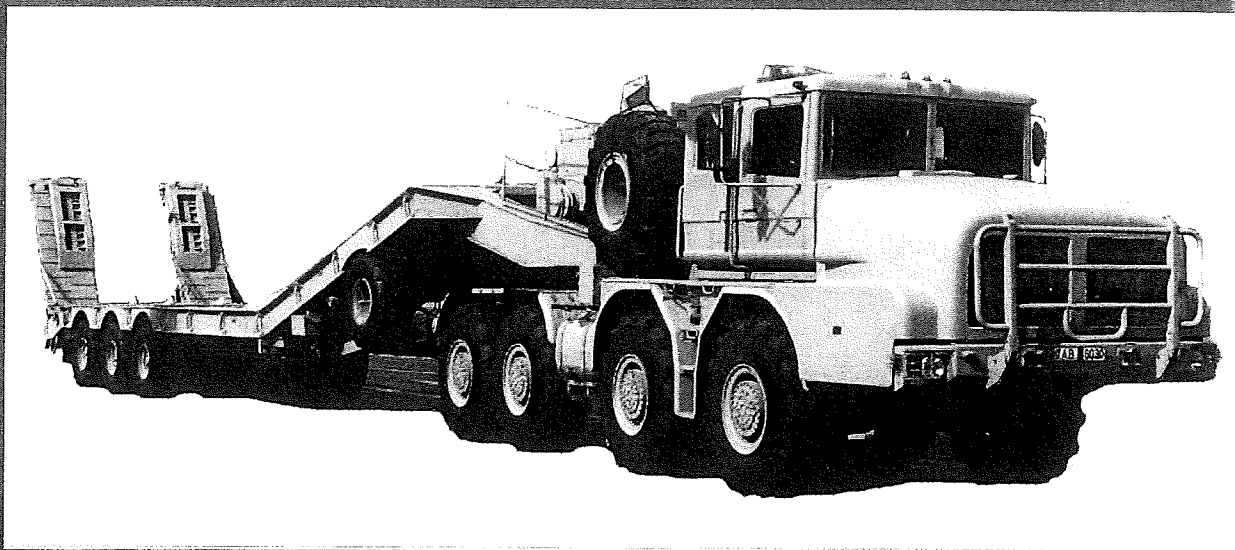


Ground Vehicle Engineering Series

Driveline Systems of Ground Vehicles

Theory and Design



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



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Preface

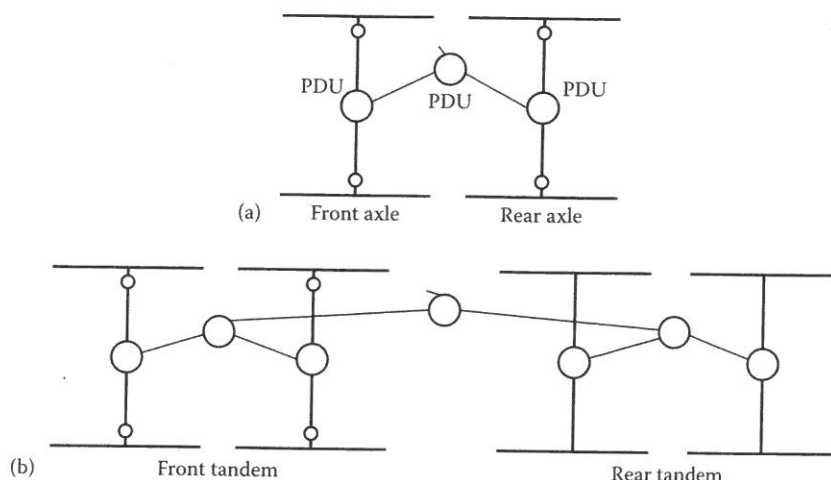
The dynamics and performance of a vehicle manifest themselves in the interaction of the vehicle with the surroundings and result from its properties such as energy/fuel efficiency, terrain mobility, tractive and velocity properties, vehicle turnability, stability of motion and handling, braking properties, 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. Broulhiet, 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 Besserlich, 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.

Dr. Vladimir V. Vantsevich
Southfield, Michigan

1980s with design of electromechanical locking and electronically controlled units. Special mention is deserved by the Auto-Lock system for locking the interaxle differential of the 6×4 truck (Rockwell International, New York), the 4MATIC electronic system for the Mercedes (Daimler-Benz, Stuttgart, Germany) passenger car, the locking device for a differential that is actuated by the difference in wheel speeds of agricultural tractors (SIGE) and many others.

Today, some automotive companies are introducing "torque-bias coupling," "torque-vectoring," and "torque management" devices to control power delivery to the front and rear axles and the left and right wheels (see Chapter 7). These driveline systems are actually mechatronic systems, and the introduction of such mechatronic designs is an epoch-making step in driveline system design. The mechatronic driveline systems are more "flexible" and proactive in distributing the engine power to the driving wheels than automated mechanical systems, e.g., the different limited-slip differentials, mechanically/electronically lockable differentials, viscous clutches, NoSPINs, on-demand systems and many others.

At the very beginning of the development of driveline systems and PDUs, the sole purpose was improving the mobility of the vehicles. Today an increasing number of OEMs and suppliers recognize the fact that vehicle operational properties such as tractive and velocity properties, stability of motion, turnability, handling, braking properties highly depend on characteristics of driveline systems that distribute power to the driving wheels. It is important to emphasize that the fuel economy and safety of vehicles that are vehicle consumer properties also depend to a large extent on driveline system designs. For this reason, driveline systems for distributing the power to the driving wheels should be designed with consideration of their combined effect on many of the vehicle operational and consumer properties.

This book is concerned with problems of driveline design precisely from the point of view of their combined effect on the performance and dynamics of wheeled vehicles.

1.2 Classification of Driveline Systems and Power Dividing Units

Depending on the manner of power transmission, all drives can be classified as electrical, hydraulic, mechanical, and hybrids. This section examines in detail mechanical driveline systems, including those of vehicles with different steering systems. Electronically controlled mechanical driveline systems are defined as mechatronic driveline systems. When speaking about mechanical and mechatronic driveline systems, many publications as a rule refer solely to the wheel formula, and at times adding information on types of the differentials. These data are clearly insufficient for complete description of driveline systems and for understanding their integration within the overall design of the vehicle. After all, frequently even vehicles of the same type use different mechanisms: symmetrical and asymmetrical differentials, positive locking engagement, self-locking differentials, limited slip differentials, free running clutches, viscous clutches, etc. This is particularly intrinsic to off-road vehicles. Thus, the driveline system the International Harvester XM-409 was fully differential with redundant locking. The 8×8 M.A.N. and Tatra-813 vehicles have the same driveline systems. In the latter, the distance between the axles of the front bogie (or tandem) is somewhat larger than that between the axles of the rear tandem. Many vehicles use mixed systems with different coupling-unit mechanisms. For example, the

central differential of the MAZ-79091 8×8 truck is a symmetrical, bevel-gear differential with redundant locking, the interaxle drive of the rear tandem is constantly locked and the interaxle drive of the front tandem and also the interwheel drives of the front tandem axles employ symmetrical open differentials. NoSPIN type differentials are used in the interwheel drives of the axles of the rear tandem. The wheel drives of the XM-453E1 truck with an 8×8 wheel formula and with tandem arrangement of the axles employ limited slip Power-Lock differentials.

The above example demonstrates the need for a tool that would provide a detailed description of the various existing driveline systems as a part of the overall design of the vehicles, from which it will be easier to understand the reasons for using the particular driveline system design. Design engineers need such a tool for describing and representing the driveline system that they design. The SAE J1952 Standard All-Wheel Driveline Systems Classification contains definitions to be used to outline the basic nomenclature and to classify all-wheel drive concepts. Some information is also contained in the *Terrain-Vehicle Systems Standards*, worked out by the International Society for Terrain-Vehicle Systems (ISTVS).

Historically, the terms and definitions pertaining to the classification of drive schemes were developed in the course of new driveline system design. The definitions of different types of drives were worked out primarily with consideration of marketing needs rather than from the point of view of the technical substance of the systems. For example, the term permanently engaged rear-wheel drive with the on-demand engagement of the front wheels by means of the transfer case is applied to 4WD. The same term, 4WD is applied to vehicles in which the two axles are coupled by an interaxle differential in the transfer case. This means that the same term is applied to vehicles, the driveline systems of which have an entirely different effect on vehicle performance. At the same time, the term AWD (all-wheel drive) is also applied to vehicles in which the interaxle differential is combined with the interwheel differential of the front axle. Following this logic, the same vehicle could be labeled as 4WD or AWD depending on the location of the interaxle differential—in the transfer case or together with the front-axle interwheel differential. However, the location of the interaxle differential does not affect the entire vehicle's performance.

In this book, driveline systems with two, four and more driving wheels are classified from the point of view of their effect on vehicle performance. The specifics of a given arrangement are reflected by means of additional indicators that integrate the driveline system with the overall vehicle design. The effect of the driveline system on vehicle performance depends on the characteristics of the locking properties of mechanisms and subsystems of the driveline system, i.e., their ability to distribute the power among the driving wheels. The overall vehicle design layouts first introduced by P. V. Aksenov include the type and location of the driving axles within the overall arrangement of all of the vehicle's axles, the steering system, type of suspension, and dimensions of the tires of the different axles of the vehicle. Consider details of the developed classifications.

The wheel formula of all types of drivelines is designated by a single expression $2m \times 2n$, in which n is the number of the driving axles to which the engine power is transmitted, whereas m is the total number of driving and driven (not coupled to the driveline system) axles. If $m = n$, then the vehicle is called an all-wheel drive vehicle. For example, 4×4 , 6×6 , 8×8 , 10×10 , 12×12 , and 16×16 are all-wheel drive vehicles. Vehicles with different numbers of driving and driven axles, for which $m \neq n$, are known as multiwheel drive vehicles. Thus, for example, vehicles with wheel formulas 6×4 , 8×4 , 8×6 , and 14×6 are multiwheel drive vehicles. The term nonall-wheel drive is applied to vehicles with two

driving wheels. These include FWD and RWD vehicles with 4×2 wheel formula; vehicles with wheel formulas of 8×2 and 6×2 are also nonall-wheel drive vehicles.

The relationship between the driveline system and the overall vehicle design is expressed by means of the following indicators.

The drive formula gives the location of the driving axles within the overall design of the vehicle. For example, the designation 0034 corresponds to an 8×4 vehicle with the third and fourth axle powered. A 12×12 vehicle has a drive formula written as 123456, whereas a 6×2 vehicle with a rear-wheel drive is designated as 003.

The axle formula symbolizes the number of axles situated in a row. For example, a vehicle with four axles (let us say, 8×8 , 8×6 , 8×4) that form two tandems have an axle formula of 2-2, whereas vehicles with four axles in which the second and the third axles are located close to one another have the axle formula 1-2-1. If a vehicle has wheels of different dimensions on the different axles, then the height of numbers in the axle formula should be different. For example, an agricultural tractor with two axles and smaller tires on the front wheels has the axle formula 1-1.

The steering formula gives the ordinal number of the steered axle. For example, the steering formula for a vehicle with three axles in which the second and third axles form a tandem, whereas the front axle is steered, is 1-00. A vehicle with two axles, of which the front axle is steered, has a steering formula of 1-0. For articulated vehicles, additional designations are provided in the steering formula:

- v , for an articulated trailer without control
- $\frac{v}{c}$, for an articulated trailer with control
- s , for a fifth wheel (a tractor-semitrailer combination)

For example, the steering formula $0\frac{v}{c}0$ corresponds to an articulated vehicle with two nonsteered axles and that is able to take turns by means of a controlled relative rotation of two segments of the vehicle about a vertical hinge. Steering systems are depicted graphically in Table 1.6.

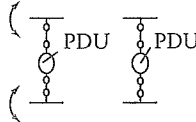
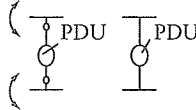
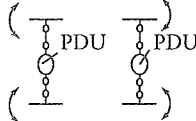
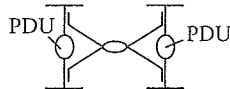
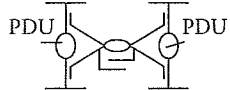
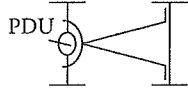
In this book, the systems that distribute the power to the wheels are defined by the concept of PDUs. Within the context of their effect on the vehicle performance, PDUs are classified by the attributes of their locking properties, i.e., on the basis of their effect on the distribution of power between the output shafts. The examples shown in Figure 1.33 illustrate types of PDUs, one of which requires additional explanation. These are planetary gear sets with two or more than two degrees of freedom and locking coupling. This is a new recently emergent type of PDUs that is used in sophisticated driveline systems. The designs of such PDUs include open differentials with additional planetary rows and locking couplings. The couplings consist of controllable friction, magneto-rheological or other clutches. This is concerned to one or another measure with virtually all types of PDUs shown in Figure 1.33.

To graphically represent the various PDUs, Table 1.7 presents designations for the most typical designs. Here there is no need to use different symbols for PDUs of the same type. For example, the same symbol \otimes is used for all the limited slip differentials some of which are shown in Figure 1.33 for illustration purposes. Instead of using a large number of symbols, it is proper to write out which limited-slip differentials are used on the given vehicle. This approach is taken because a large number of designs with the most different features have already been produced and are under development.

In addition to PDUs, graphic representations of driveline units are described by Power Transfer Units (PTUs, see SAE J1952 Standard). However, in the present book the

TABLE 1.6

Steering Systems

| Type of System | Designation | Steering Formula |
|---|--|------------------|
| Drive-steer and nonsteer articulated axles with independent suspension |  | 1-0 |
| Drive-steer and nonsteer conventional axles with dependent suspension |  | 1-0 |
| Drive-steer articulated axles with independent suspension |  | 1-1 |
| Lag hinge without steering: v |  | $0-\frac{v}{0}$ |
| Lag hinge with steering: $\frac{v}{c}$ |  | $0-\frac{v}{c}$ |
| Fifth wheel hinge without steering: s Notice: Second axle is driven (nondriving) |  | $0-\frac{s}{0}$ |

definition of this term has been extended: PTUs are used for controlling power flow between their input and output elements. Typical graphical symbols of PTUs are presented in Table 1.8.

Using the PDUs and PTUs from Tables 1.7 and 1.8 it is possible to compose different driveline systems that shall be termed simple, combined, and integrated. Definitions of these systems are given in Figure 1.34. A simple driveline system may be exemplified by the drive of a 4×4 automobile with open differentials in the driving axles and an open differential in the transfer case. This means that in a simple driveline system identical mechanisms are used in all the PDUs. Should at least one of the differentials of the above vehicle be a limited-slip differential, then such a driveline system will be known as a combined system. If the vehicles under study are equipped, for example, by a traction control system, then their systems will be known as integrated, since the driveline system is functionally coupled to the braking system.

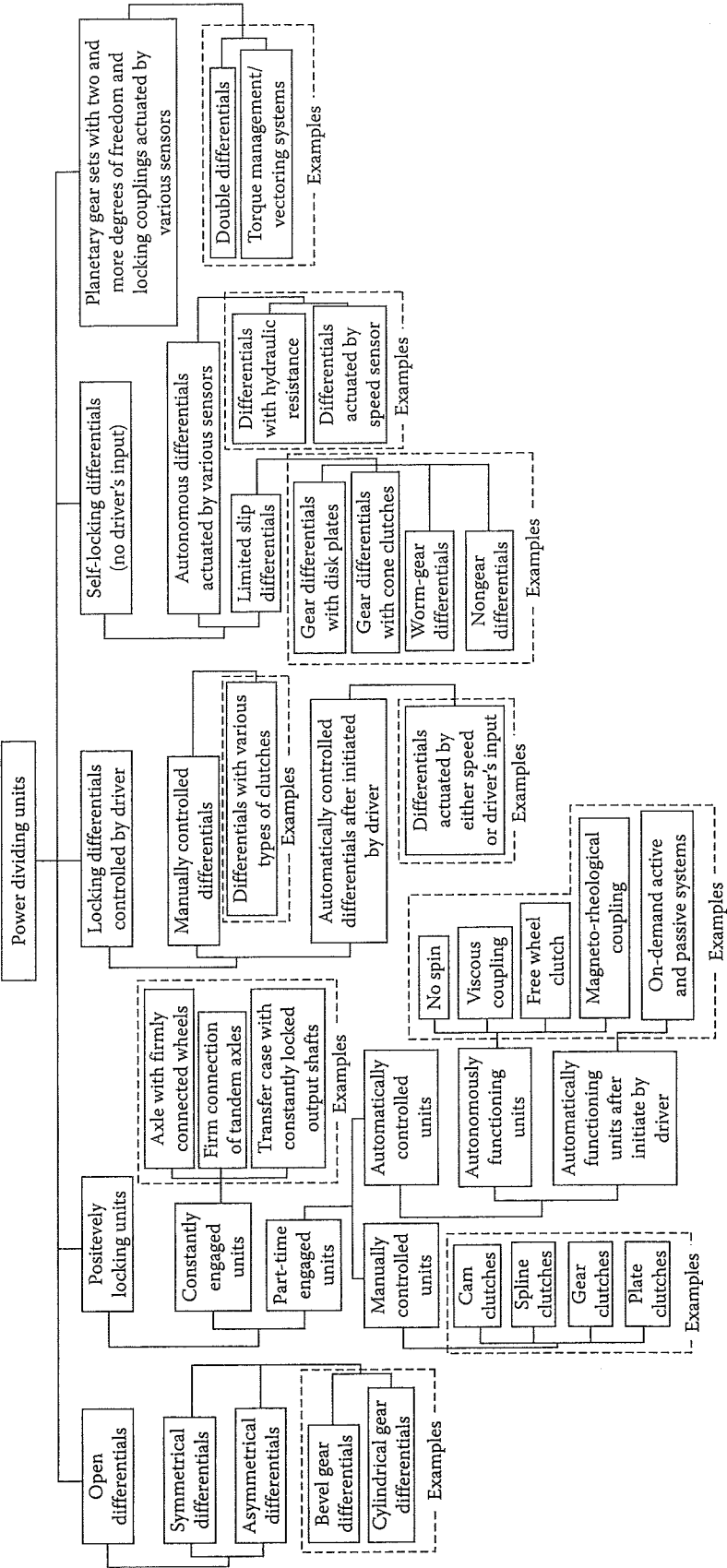
















FIGURE 1.33
Major types of PDUs.

TABLE 1.7

Symbols of Mechanisms of Power Dividing Units

| Mechanism in PDU | Designation |
|--|---|
| Symmetrical open (free) differential |  |
| Symmetrical locking differential |  |
| Asymmetrical open (free) differential |  |
| Asymmetrical locking differential |  |
| Symmetrical limited slip differential |  |
| Asymmetrical limited slip differential |  |
| Symmetrical differential with viscous or rheological clutch |  |
| Asymmetrical differential with viscous or rheological clutch |  |
| Overrunning self-locking differential (similar to NoSPIN) |  |
| Automatic engagement/disengagement of one of the output shafts (e.g., on-demand systems) |  |
| Freewheel (overrunning) clutch |  |
| Constantly locking engagement of the output shafts |  |
| Nonconstant engagement with manual disengagement of one of the output shafts |  |
| Torque vectoring (torque management) device based on planetary gear sets with two and more degrees of freedom and locking couplings/mechanisms |  |

Notes:










- Intelligence symbols   (SAE J1952 Standard) may be added to the basic symbol to indicate that the PDU responds automatically to signals from one or more external control systems.
- Additional abbreviations explains   symbols. Examples: AL/AS, antilock and antispin brake; IA/IW, interaction between interaxle and interwheel PDUs. The following abbreviations describe an interaction between driveline system (DL) and other vehicle systems and sensors: DL/DT, drivetrain (engine and transmission) system; DL/ST, steering system; DL/SS, suspension system; DL/BR, brake system; DL/LoA, longitudinal acceleration sensors; DL/LaA, lateral acceleration; DL/YAW, yaw (rate) sensors; DL/RO, rollover sensors.

TABLE 1.8
Symbols of Power Transfer Units

| Power Transfer Unit | Designation |
|---|---|
| Multiple plate clutch |  |
| Multiple plate clutch with viscous or rheological fluid |  |
| Automatic or manual disconnect (e.g. disconnect hub) |  |
| Hydrostatic drive |  |
| Electric drive |  |

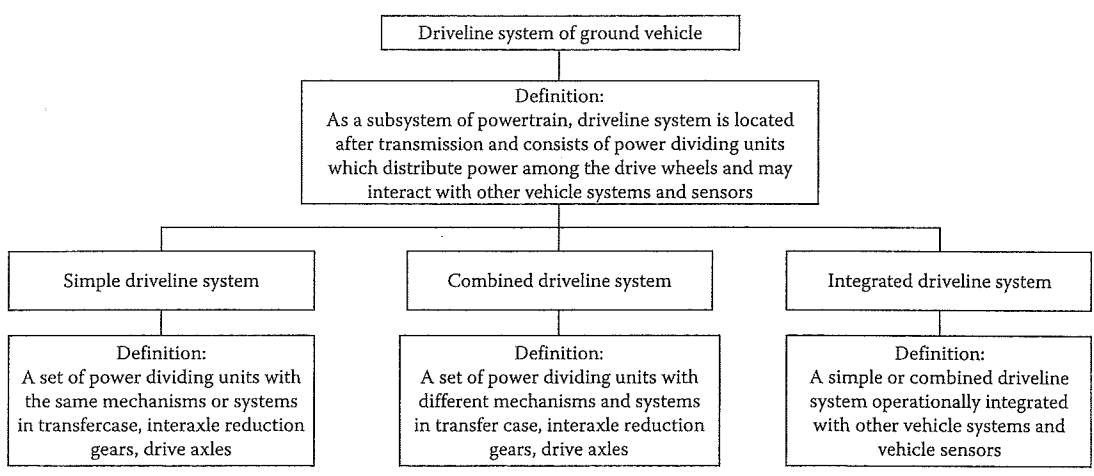


FIGURE 1.34
Simple, combined, and integrated driveline systems.

Note that the number of PDUs for a vehicle with a single engine and an axle system is always by one less than the number of the driving wheels. For example, a 12 × 12 vehicle has eleven PDUs. It is useful to note in connection with this that vehicles with a single driving axle may have either simple or integrated driveline systems, since they have only one PDU between the left and right driving wheels.

For characterizing wheel driveline systems as a part of the powertrain it is convenient to use powertrain layouts that are composed of gears, shafts, connected by couplings, locking clutches, splined and keyed joints, hinges and bearings. Table 1.9 lists the most typical elements. Certain other elements, not contained in Table 1.9, can be easily recognized in the layouts presented in the book.

TABLE 1.9

PTU Elements for Kinematic Diagrams




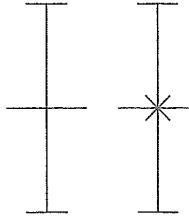
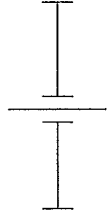
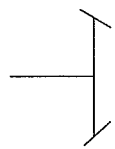
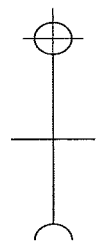

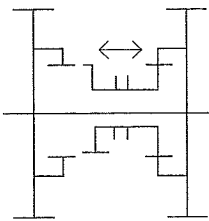

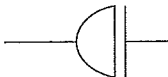

| Power Transfer Unit Element | Designation |
|--|---|
| Shaft, axle |  |
| Sliding bearing |  |
| Rolling bearing |  |
| Cylindrical gears firmly connected to shafts |  |
| Cylindrical gears freely rotating on shafts |  |
| Bevel gears firmly connected to shafts |  |
| Worm—gear set |  |
| Brake |  |

TABLE 1.9 (continued)
PTU Elements for Kinematic Diagrams

| Power Transfer Unit Element | Designation |
|-----------------------------|--|
| Gear-type coupling |  |
| Cam-type coupling |  |
| Universal joint |  |
| Constant velocity joint |  |

Now examine examples of the use of the suggested classification of driveline systems in conjunctions with the general vehicle design.

Table 1.10 shows typical examples of general engineering layout and driveline systems of 4×4 agricultural tractors. A lockable interaxle driveline that provides for disengagement of one of the axles is widely employed both on articulated-frame tractors (e.g., K-710 or T-150K, positions 1 and 2 in Table 1.10) and tractors with steering wheels (MTZ—Minsk Tractor Works, LTZ—Lipetsk Tractor Works, positions 3, 6, and 7). Identical-wheel tractors (Profi Trac, position 4) are designed with interaxle symmetrical locking differentials. John Deere 3640 tractors with nonidentical front- and rear-axle wheels (position 5) make use of interaxle asymmetrical locking differentials. As to interwheel PDUs, the examples listed in Table 1.10 correspond to the above statistical data showing wide use of locking and self-locking (limited-slip) differentials.


Figure 1.35 shows the kinematic layout of an articulated tractor listed under No. 1 in Table 1.10. This articulated tractor has overrunning self-locking differentials (similar to NoSPIN) in its driving wheels, which is shown by the  designation. The primary traction axle here is the front one. The rear axle is engaged and disengaged by a mechanical clutch M (see Figure 1.35).

Figure 1.36 shows the kinematic layout of the powertrain of the T-150K articulated tractor (Table 1.10, position 2). The primary driving axle of this tractor is in the rear, whereas the front axle is coupled mechanically by means of gear 19 that is capable of sliding along the shaft. The tractor is equipped with limited-slip differentials with disk-type clutches in the driving axles.

The powertrain layout of the MTZ-82 tractor, position 6 in Table 1.10, is shown in Figure 1.37. The front-axle differential P with floating pinion fingers (see Chapter 4) is a limited-slip device, whereas the rear axle differential D is locked by hydraulically controlled

The course stability highly affects the motion of the vehicle along its specified path. In the case of unsatisfactory course stability, the driver must always be ready to change the direction of motion caused by deviation from the specified path. When the course stability is excessive, the driver must exert an additional effort to change the direction of motion.

Loss of lateral stability manifests itself in lateral slip (or skidding) of the vehicle that may subsequently result in rollover about the x -axis, i.e., loss of stability in transverse rollover.

Motion along the specified path is virtually independent of the stability to longitudinal rollover about the y -axis.

The critical velocity V_{cr} , upon reaching which the vehicle motion becomes unstable is the most prevalent criterion of stability assessment. The value of the vehicle's V_{cr} is usually examined from analysis of the values of coefficients of the gripping force utilization factor K_μ of all the driving wheels:

$$K_\mu = \frac{\sqrt{F_x^2 + F_l^2}}{\mu_{px} R_Z} \quad (1.119)$$

The lower the value of K_μ , the higher the gripping potential of the wheels and the greater the probability that the vehicle will move in the curved path set by the driver. It is usually assumed that lateral skid of a wheel occurs at $K_\mu > 0.5$.

The stability of motion is also assessed on the basis of the following

1. Angular velocity r of vehicle about the vertical axis, known as the yaw rate, rad/s or deg/s
2. Lateral velocity V_y and lateral acceleration a_y of the center of gravity
3. Lateral roll angle of the sprung mass γ_1

The effect of the driveline system on motion stability manifests itself in the fact that the redistribution of the circumferential forces among the driving wheels affects the lateral wheel forces F_l (see Section 1.3.4) and hence the value of K_μ from formula (1.119). This may cause skid of individual wheels and then of individual axles and of the entire vehicle.

Controlling the redistribution of circumferential forces between the axles and also between the left and right wheels, allows governing the yaw rate, the lateral velocity and lateral acceleration of the vehicle. These means make it possible to prevent a situation when the lateral roll angle γ_1 would reach its critical value.

1.5.5 Handling of the Vehicle

Handling of the vehicle is here a term applied to the ability of the vehicle to respond to the steering input with the required precision and speed. The handling of a vehicle depends to a large extent on its turnability and stability. In fact, the precision and speed of responding to the steering input should differ depending on whether the vehicle is unstable or is overstable. Overstability also reduces the vehicle's ability to take a turn, which is detrimental to its turnability. Under these conditions the driver must devote additional emotional power to making the turn. This has a negative effect on the ease of handling and on safety that the consumer expects of the vehicle.

With reference to the above, handling, as an operating property of the vehicle may even be excluded from the list properties that depend on the driveline system design. It is

assumed here that the features of driveline systems that ensure the required stability and turnability of the vehicle simultaneously satisfy the handling requirement. Such an approach can be applied to off-road equipment that moves at relatively low velocities. If, however, it is necessary to assess the handling of a vehicle directly, this is done on the basis of the ratio of the yaw rate r to angle of turn δ of steering wheels, which is known as the handling sensitivity (i.e., the sensitivity of the vehicle to the steering input by the driver):

$$S_e = \frac{r}{\delta} \quad (1.120)$$

Figure 1.81 shows typical curves of handling sensitivity S_e as a function of the forward speed V_x .

Straight line 1 corresponds to a vehicle with neutral turnability (neutralsteering). If the vehicle exhibits oversteering (curve 2), then the value of S_e tends to infinity and the vehicle cannot be handled because of loss of stability: the speed attains the critical value of V_{cr} . In the case of understeering (curve 3) S_e attains some maximum value upon an increase in speed. Steady-state sensitivity is known as

$$S_e^{st} = \frac{1}{\delta R_a} \quad (1.121)$$

and unsteady-state (dynamic) sensitivity is

$$S_e^{dn} = \frac{\partial S_e^{st}}{\partial t} \approx \frac{S_e^{st}}{t_R} \quad (1.122)$$

where t_R is the time delay in the vehicle's reaction to a quick turn of the steering wheel (vehicle response time). The value of t_R depends on the play and elasticity of the steering system, the ability of the suspension and tires to generate lateral reactions F_l in the contact patches between the tires and the road. Driveline systems affect the lateral reactions of tires by means of redistribution of torque among the wheels and in this way they also affect the magnitude of time t_R .

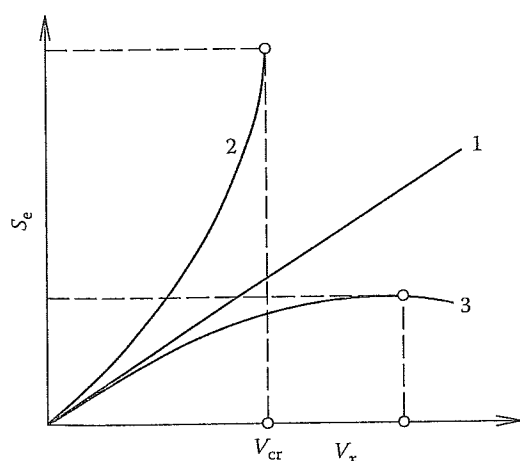


FIGURE 1.81
Handling sensitivity.

In addition to sensitivity S_e and the time t_R , the handling of a vehicle is assessed by the following

1. Speed of self-return of the steered wheels upon completing the turn
2. Steering-wheel torque as a function of the lateral acceleration a_y and path curvature $1/R_a$
3. Transient time t_s needed to stabilize the motion when completing lane change
4. Roll angle γ_l of the vehicle's sprung mass as a function of the lateral acceleration a_y

Some investigators classify the study of vehicle handling modes into three stages:

1. The primary handling stage that is primarily linear
2. The secondary handling stage, which is one in which the handling becomes substantially nonlinear
3. The final handling stage, which is the last stage that corresponds to higher lateral accelerations (from 0.5g for commercial vehicles to 0.8g for passenger cars and to even higher values for racing cars)

It follows from the material presented above that the driveline systems affect several operational and consumer properties of vehicles. Here each of these properties has several evaluation criteria. Very frequently, when designing a driveline system on the basis of a criterion (criteria) representing one of the properties it is possible to worsen other properties of the vehicle. For example, locking the differential of the driving axle improves the traction-velocity properties of the vehicle, but is detrimental to its turnability, since this causes a marked increase in the turning radius R_a . For this reason the finding of optimal and close to them characteristics for the driveline system should be treated as a multi-criterion problem. The main principles of the design of driveline systems are treated in the next section.

1.6 Principles of Driveline System Design

This section focuses on the engineering principles of designing driveline systems, pertaining to determination of the optimal features of driveline systems and PDUs, investigation of the effect of driveline system on the vehicle performance and dynamics and also pertaining directly to engineering design of PDUs. No consideration is given here to the economic and manufacturing aspects of design, since it is assumed that they are considered concurrently with the design process.

Historically, driveline system design has been initially based on the method of comparative analysis. According to this approach, a number of driveline systems with various combinations of PDU mechanisms and systems could be researched analytically for a given vehicle or vehicles based on some criteria of the vehicle's properties from the point of view of its operation and customer satisfaction.

The ranges of the numerical values of these criteria are usually established and the values themselves are determined on the basis of computer simulation of the vehicle's

mathematical model with the given driveline system. Such an analysis of the vehicle criteria aids in applying analytical and experimental analysis to select the best of the several driveline systems under consideration for the given vehicle. Comparative analysis also enables engineers to analytically and experimentally compare different vehicles with the same or different driveline systems.

However, the application of the above design research approach in no way ensures that the selected driveline system endows the vehicle with the optimal/desired performance, within the specified range of values of these criteria. It is indeed possible that the best driveline system and the optimal combination of PDUs are to be found outside the researched selection of drivelines and sets of PDU mechanisms and subsystems. Hence, the method of comparative analysis does not provide prerequisites and conditions sufficient for developing better driveline systems.

The importance and the necessity of further development of advanced approaches and methodologies in the field of driveline systems design remain undiminished. The urgency of the need for a new scientifically founded methodology also stems from recent engineering advancements. Some automotive companies are presently working on torque-bias couplings, torque-vectoring, and torque management devices to control torque distribution to the drive axles and wheels. These are mechatronic systems, and designing mechatronic driveline systems is to be founded on a new methodological basis.

This section of the book describes a methodology that includes the key principles of all-wheel driveline system design and is based not on wheel torque vectoring but on wheel power management as a part of a broader analytical approach. The proposed principles pertain to the optimization of power distribution among the driving wheels in both rectilinear and curvilinear vehicle motion. This new methodology is based on inverse dynamics, consisting in treated aspects of vehicle dynamics as an inverse dynamics problem. Under this approach, forces acting on a mechanical system are determined for the given/required kinematic parameters, e.g., program of motion. To explain this in simple terms, the equation of motion of a body is given below in the form of Newton's second law:

$$\sum_{i=1}^s \vec{F}_i = m\vec{a} \quad (1.123)$$

In applying inverse dynamics, the acceleration \vec{a} is assigned first, and then the forces $\sum_{i=1}^s \vec{F}_i$ acting on the body with mass m needed to provide it with the required acceleration are synthesized. As for vehicles, these forces are the foundation for researching vehicle operational properties, namely for optimizing the criteria for these properties and then for designing optimal driveline systems.

The following example will serve for illustrating many of the applications of inverse-dynamics analysis. Curve 1 in Figure 1.82 describes the variation in the vehicle's speed as it is being accelerated to the specified value. Let it be required to improve the vehicle acceleration performance in such a manner that the velocity V_x in the course of acceleration conform to curve 2. This requires that acceleration a_x defined by function $V_x = f(t)$ from curve 2, be used for determining the circumferential forces of the wheels $F_{xi}^{(c)}$, ($i = 1, n$), from Equation 1.123. These forces should then be used for designing the vehicle's systems including the driveline system.

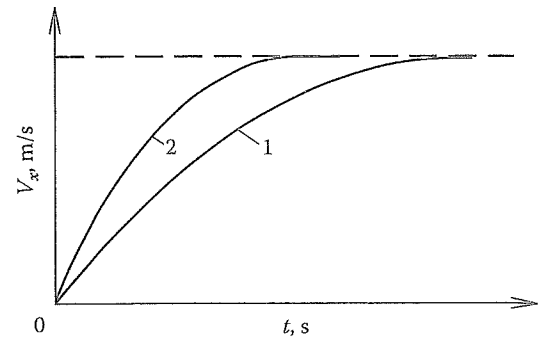


FIGURE 1.82
For acceleration performance analysis.

Summing up, the proposed methodology:

1. Provides a way to optimally manage power distribution to the wheels and to determine the optimal characteristics of driveline systems based on operational properties criteria
2. Links these operational properties optimization to improvement of vehicle dynamics
3. Leads to the required/desired vehicle performance and engineering efficiency.

These principles can be formulated as follows

Principle 1. Specify the required kinematic parameters of a vehicle in motion and treat vehicle dynamics as the inverse dynamics for the purpose of determining the total power required for the vehicle's motion. Find optimum combinations of the total power distribution to the driving wheels that conform to the specified kinematic parameters of the vehicle in the specified modes of operation and under the specified road/terrain conditions.

As seen from Principle 1, the kinematic parameters of motion should be assigned first for the given vehicle's operational modes and conditions of motion. Modes of operation and road/terrain conditions stem from the vehicle's intended use. Passenger cars and earth-moving machines work in different modes and under different conditions. The required kinematic parameters may be assigned based on the vehicle's design specification.

As discussed earlier, vehicle dynamics influences vehicle performance. To better represent this influence, Principle 1 proposes a new approach to determining the total power required for the vehicle motion and to optimizing power distribution to the driving wheels. The approach is based on treating vehicle dynamics as the inverse dynamics: forces acting on the driving wheels of a vehicle (see formulae (1.123) and (1.74)) are determined using the required kinematic parameters represented by the acceleration in the above formulae. These forces are used to determine the total power needed for the vehicle's motion and for finding the power distribution to the driving wheels.

Principle 2. The optimum combinations of power distributions to the driving wheels should also be determined by providing the extrema values of vehicle operational properties criteria in the specified modes of operation and under the given road/terrain conditions. There are three modes of operation and these are presented in Table 1.19. A list of operational properties and their criteria were given in Section 1.5 (see Figure 1.73).

It is hereby suggested that a new term—"power vectoring" or "power management" be used in determining the optimum power distribution to the driving wheels. Such an approach addresses both vehicle dynamics and vehicle performance issues. Indeed, optimum combinations of power distributions to the driving wheels, which conform to the extrema values of some vehicle performance criteria, can be used for synthesizing laws and algorithms for controlling driveline mechanisms and subsystems of a particular vehicle. Moreover, optimum power distributions to the driveline wheels create an efficient way for designing new-concept driveline systems and mechanisms.

It should be noted that the wheel power optimization in Principles 1 and 2 is a constrained multicriteria optimization. In practice, some wheel power distributions that are optimal from the point of tractive and velocity properties can be detrimental to other vehicle operational properties such as turnability and handling. Some power distributions may be optimal in terms of vehicle operational properties, but they could not satisfy the kinematic requirements put to vehicle motion. For this reason, when pursuing Principle 2, the task of determining the extrema values of the criteria can be replaced with finding the required/specified values of these criteria.

Principle 3. Based on the optimal wheel distributions, synthesize and establish optimal characteristics for a hypothetical driveline system.

The driveline system has been termed hypothetical, because this principle is implemented at a stage when the vehicle does not yet have a driveline system. At this point, the only available information is the optimal wheel power distribution. This distribution is the basis for synthesizing optimal characteristics for so called hypothetical driveline systems.

Also, Principle 3 does not set up rules for designing a particular driveline system that could be either mechanical or a mechatronic one. Because of this, Principle 3 does not limit engineers, but gives them another degree of freedom in designing driveline systems with new characteristics. Indeed, these characteristics can be considered not only as torque biased, but also as control algorithms for individual wheel power control. Such new characteristics may lead to driveline system designs that are based on novel concepts of operation. At this stage, engineers and researches should thoroughly research achievements in fundamental science that can be used for driveline applications. As an example, viscous clutches can be regarded as a driveline application emerged from fundamental research of non-Newtonian fluids.

Principle 4. Once the optimal driveline system characteristics are synthesized, design a driveline system, simple or combined or integrated, that implements the optimal or near optimal characteristics in a set of PDUs, which, if needed, interact with other vehicle systems.

The mechanisms that implement the optimal characteristics in given PDUs need not necessarily always be new designs. Sometimes, mechanisms with the required optimal or near optimal characteristics are available off the shelf. The optimality of these characteristics should be validated following the research done under Principle 4. Such validation can be performed by means of a performance analysis of a vehicle with the new optimal driveline system.

It is clear from principles 1 to 4 formulated above that a vehicle with the newly-designed driveline system will have an optimal power distribution to the driving wheels, and the vehicle will move with the required kinematic parameters in the given operational modes

| Prin- ciple | Algorithm major steps | | | |
|----------------|---|--|---|---|
| | #1 | #2 | #3 | #4 |
| #1 | Based on inverse dynamics approach develop a math model of a vehicle without a driveline system and determine the total wheel power under the required vehicle kinematics | Optimize power distributions among the drive wheels using criteria of vehicle operational properties and vehicle kinematics requirements | Synthesize optimal characteristics for vehicle power dividing units | Design power dividing units which provide optimal characteristics found in step 3 |
| #2 | | | | |
| #3 | | | | |
| #4 | | | | |

FIGURE 1.83

General algorithm for driveline system design.

and road/terrain conditions. Finally, the vehicle will manifest its optimal operational properties and performance and therefore, will operate at higher engineering efficiency level.

The four principles presented above include the following major key-points:

- Inverse vehicle dynamics approach to determining the total wheel power required for motion with the given kinematic parameters.
- Wheel power optimization based on the criteria of vehicle operational properties and vehicle kinematics requirements.
- Synthesis of optimal characteristics of vehicle PDUs.
- Design of a driveline system and PDUs that provides optimal distribution of power to the wheels and better vehicle performance, and the required/desired kinematic parameters of vehicle motion.

Principles 1 through 4 and the general algorithm from Figure 1.83 that represents the principles were verified and validated in many research projects.

Chapters 6 and 7 present various applications of the principles to mechanical and mechatronic driveline systems design. Chapters 2 through 5 present analytical methods and their applications to designing and researching various PDUs including open and locking differentials, viscous clutches, NoSPINs, on demand systems, etc. The material presented in these chapters is important for carrying out the fourth step of the algorithm from Figure 1.83.