
All-Wheel Driveline Mechatronic Systems: Principles of Wheel Power Management

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ABSTRACT

All-wheel driveline systems with electronic torque control on each and all wheels, torque vectoring and torque management devices, hybrid electro-mechanical systems, and individual electro (hydraulic) motors in the wheels have been gaining a bigger interest in the industry for recent years. The majority of automotive applications are in vehicle stability control that is performed by controlling the vehicle yaw moment. Some devices also improve vehicle traction performance.

The proposed paper develops a methodology that includes the key-principles in all-wheel driveline systems design and is based on the wheel power management as a broader analytical approach. The proposed principles relate to the optimization of power distributions to the drive wheels in both rectilinear and curvilinear vehicle motion. Inverse dynamics is the basis for the developed methodology.

Combinations of optimal power distributions at the drive wheels and proactive estimation of the road conditions (friction coefficient estimation) lead to developing adaptive control algorithms for a new generation of mechatronic driveline systems.

Mechatronic systems designed with the proposed methodology can improve not only stability of vehicles, but can provide vehicles with better operational properties such as traction/velocity properties, energy/fuel efficiency, vehicle turnability, and handling.

INTRODUCTION

The driveline system may be defined as it is introduced in Fig. 1. There are two key elements in this definition: the driveline system location (a part of the powertrain located after transmission), and the purpose of the driveline system (to distribute power among the drive wheels). The subject of this paper is to present principles for optimizing wheel power distributions and then for designing optimum driveline systems that provide vehicles with best performance compare what other driveline systems can do.

Driveline systems design as a constituent of the vehicle design and vehicle dynamics analysis started to take its shape in the early 20th century. The first

publication, as far as is known, was written in 1905 by Prof. N. E. Zhukovsky [1]. His work relates to traction force and slip analysis at the wheels of a solid axle in the drive and driven modes. Today, driveline design has gained knowledge and experience through works of many engineers, researchers, and companies.

However, the importance and the necessity of further developments of advanced approaches and methodologies in the area of driveline systems design are still in the engineering agenda. The urgency for a new scientifically founded methodology is also dictated by recent engineering achievements. Today, some automotive companies are introducing "torque-bias couplings", "torque-vectoring" and "torque management" devices to control torque delivery to the front and rear axles and left and right wheels [2, 3, 4, 5, 6, 7, 8, and 9]. These driveline systems are actually mechatronic systems, and the introduction of such mechatronic designs opens an epoch-making step in designing driveline systems. The driveline mechatronic systems are more "flexible" and proactive in distributing the engine power to the drive wheels than automated mechanical systems, e.g. numerous of limited slip differentials, mechanically/electronically lockable differentials, viscous clutches, no spins, on-demand systems, and many others.

Another contemporary tendency in the driveline systems design relates to networking with other vehicle systems, such as steering system, brakes, suspension system, others. Taking this into account, driveline systems have been grouped in two categories: simple and combined systems (see Fig. 1). This two-group classification is certainly conditional. However, as will be shown, it provides a deeper understanding of interrelationships between driveline systems design and vehicle design and performance improvement.

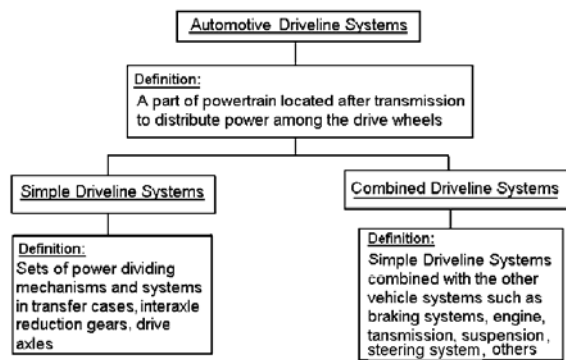


Fig. 1. Definition of driveline system

A simple driveline system includes a set of mechanisms and subsystems installed in power-dividing units (PDUs). Typically, a PDU has one input and two outputs. These units include transfer cases, interaxle reduction gears, and drive 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 drive wheels lowered by one. For example, a vehicle with four drive wheels has three power-dividing units: the first one is in the transfer case, two more units are installed on the front and rear axles (see Fig. 2). As seen from this, combinations of mechanisms and subsystems that could be employed for these three PDUs are practically uncountable.

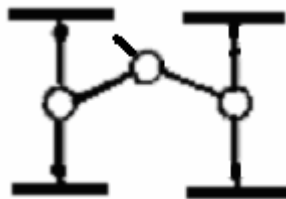


Fig. 2. Vehicle with two drive axles: driveline system layout

Which combination of mechanisms and subsystems in a vehicle's PDUs (read "the driveline system") is optimal for a particular vehicle? How to optimize the set of the PDUs within its relationships with other vehicle system when designing a combined driveline system? A better way to address these issues comes from further consideration of vehicle dynamics and performance. The following section of this paper presents details.

VEHICLE DYNAMICS vs. VEHICLE PERFORMANCE AND DRIVELINE SYSTEMS DESIGN

Dynamics and performance of vehicles with four or more drive wheels result from vehicle operational properties such as energy/fuel efficiency, cross-country mobility, tractive and velocity properties, vehicle turnability, and stability of motion and handling. No doubt, these vehicle operational properties considerably

depend on total power applied to all the drive wheels. At the same time, the listed operational properties strongly depend on the distribution of total power among the drive wheels. In the given road/terrain conditions, the same vehicle with a constant total power at the drive wheels, but with different power distributions among the drive axles and left and right wheels of each axle will perform differently, that is, the criteria of the above-listed operational properties will have different quantities.

As follows from the above-stated, vehicle dynamics and vehicle performance are not equivalent to each other. Vehicle performance should be treated as a broader concept that includes both vehicle dynamics as dynamics of a vehicle in motion and the above-mentioned vehicle operational properties [10, 11, 12, 13], and, at the top, vehicle technical efficiency, that is, vehicle productivity [14, 15, 16, 17].

Below Fig. 3 lists the vehicle operational properties in conjunction with the major vehicle systems. The designing of the driveline system is to be based on criteria of the vehicle operational properties surrounded by a frame. Also, Fig. 3 explains the proposed way of designing combined driveline systems. For example, when designing a system that combines a simple driveline system with a brake-based traction control system, the criteria of smoothness of ride and braking capability should also be taken into consideration. Respectively, criteria of the vehicle operational properties that depend on the simple driveline system should also include parameters of the vehicle brake system.

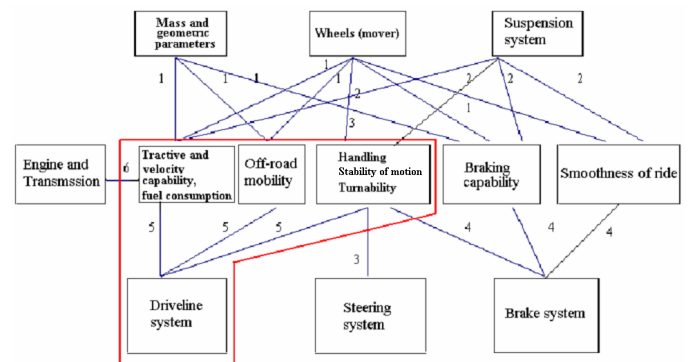


Fig. 3. Vehicle operational properties vs. vehicle systems

Based on the presented materials, one could notice that a methodology for designing driveline systems should

(a) Provide a way to optimally manage power distributions to the drive wheels and to determine optimum characteristics of driveline systems based on the criteria of the operational properties and

(b) Link these vehicle operational properties optimization with vehicle dynamics improvement and finally

(c) Lead to the required vehicle performance and technical efficiency.

Historically, the first approach to driveline system design has been based on the method of comparative analysis. According to this approach, numbers of driveline systems with various combinations of mechanisms and subsystems in PDUs could be analytically researched for a given vehicle using some criteria of the operational properties of the vehicle. Usually, numerical values of the criteria are determined and ranged on the basis of computer simulation of the vehicle mathematical model with the given driveline systems. Such analysis of the vehicle criteria helps pick up a better driveline system from the given ones. However, having accepted the described research approach, it is impossible to assert that the chosen driveline system provides the vehicle with the optimal/desired performance, which is consistent with the extreme values of the criteria. Indeed, the best driveline system and the optimal combination of PDUs could be out of the researched drivelines and the sets of mechanisms and subsystems in the PDUs. Hence, this method of comparative analysis does not create sufficient prerequisites and conditions for developing better vehicle driveline systems.

In this paper, a different methodology to designing driveline systems is proposed and is named the methodology of wheel power management and driveline system synthesis. The developed methodology treats vehicle dynamics as the inverse dynamics. In the inverse dynamics, forces acting on a mechanical system are determined for the given/required kinematic parameters. To explain this in very simple terms, the equation of motion of a mechanical system is given below in the form of Newton's second law:

$$\sum_{i=1}^n \bar{F}_i = m\bar{a} \quad (1)$$

In the inverse dynamics, the acceleration $\bar{a}$ is assigned first, and then the forces $\sum_{i=1}^n \bar{F}_i$ acting on the system with mass of m are synthesized to provide the system with the required acceleration. These forces are the foundations for researching vehicle operational properties, namely for optimizing criteria of the vehicle operational properties.

PRINCIPLES OF WHEEL POWER MANAGEMENT

Based on the above-presented material, the first principle may be formulated as follows:

Principle 1. Specify required kinematic parameters of a vehicle in motion and treat vehicle dynamics as the inverse dynamics with the purpose to determine the total power required for the vehicle motion and also to find optimum combinations of the total power distribution to the drive wheels that correspond to the given kinematic parameters of the vehicle in the given modes of operation and in the given road/terrain road conditions.

As seen from Principle 1, the kinematic parameters of motion should be assigned first for the given vehicle operational modes and conditions of

motion. Modes of operation and road/terrain conditions come from the purpose of a vehicle. Passenger cars and earth moving machines work in different modes and conditions. The required kinematic parameters may be assigned based on the vehicle specification for design.

As discussed earlier in this paper, 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 distributions to the drive wheels. The approach is based on treating vehicle dynamics as the inverse dynamics. It means that forces acting on a vehicle (see formula (1)) are determined using the required kinematic parameters represented by the acceleration in the same formula. These forces are used to determine the total power for the vehicle motion and to find power distributions to the drive wheels.

Principle 2. The optimum combinations of power distributions to the drive wheels should also be determined in a way of providing the extreme values of criteria of vehicle operational properties in the specified modes of operation and in the given road/terrain conditions (see Fig. 3).

Determining optimum power distributions to the drive wheels coins a new term of "power vectoring" or "power managing" being suggested in this paper. Such an approach addresses both vehicle dynamics and vehicle performance issues as proved in references [13, 14, 15, and 16]. Indeed, optimum combinations of power distributions to the drive wheels, which conform to the extreme 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 drive wheels create an efficient way for designing new concept driveline systems and mechanisms.

Take note that the wheel power optimization in Principles 1 and 2 is a multi-criterion constrained optimization. In practice, some wheel power distributions that are optimal from the point of the tractive and velocity properties can bring harm 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 to vehicle motion. For this reason, when pursuing Principle 2, the extreme values of criteria may be substituted with the required/given values.

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

The driveline system has been named a hypothetical one, because this principle is implemented at a stage when there is not any driveline system at the vehicle. At this point, the optimal wheel power distributions are in disposal only. These distributions are the basis for synthesizing optimal characteristics for so called hypothetical driveline systems.

Also, Principle 3 does not set up regulations for designing a particular driveline system that could be

either mechanical or mechatronic one. Because of this, Principle 3 does not limit engineers, but gives them another degree of freedom in creating new driveline characteristics. Indeed, these characteristics can be considered not only as torque biases, but as logic control algorithms. Such new characteristics may lead to driveline system designs that are based on novel concepts of operation. At this stage, engineers and researchers should thoughtfully look for achievements in fundamental science that can be used for driveline applications. As an example, viscous clutches can be pointed as a driveline application of fundamental research of non-Newtonian fluids.

Principle 4. Having the optimal driveline system characteristics synthesized, design a driveline system, simple or combined, that implements the optimal or near optimal characteristics in a set of power dividing units which, if needed, interact with other vehicle systems.

When implementing the optimal characteristics in a set of mechanisms for the vehicle's PDUs, the mechanisms should not necessarily always be new designs. Sometimes, mechanisms with needed optimal or near optimal characteristics are available in the market. A validation of the optimal characteristics should follow the research done within Principle 4. Such validation can be performed by doing a performance analysis of a vehicle with a new optimal driveline system.

From the formulated Principles 1 to 4, it is clear that a vehicle with the designed driveline system will have optimal power distributions to the drive wheels, and the vehicle will move with the required kinematic parameters in the given operational modes and road/terrain conditions. Finally, the vehicle will display its optimal operational properties, performance, and technical efficiency.

Principles 1 to 4 have been verified and validated in many research projects. A mechatronic combined driveline system of a heavy-duty truck with one drive axle is an example (Fig. 4).

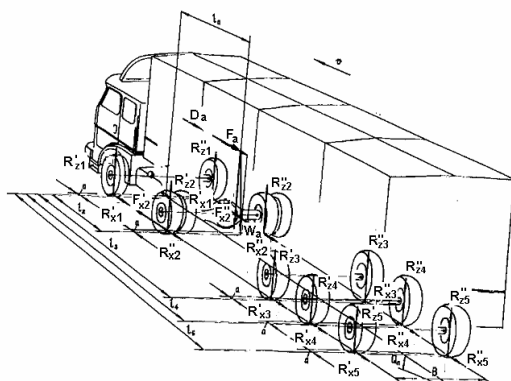


Fig. 4. Truck free-body diagram

When the truck accelerates from rest to the given speed in a straight line with different road conditions for the right and left drive wheels, the difference between the truck running gear efficiency with optimal power at the

drive wheels, η_{x*}^{tr} , and the running gear efficiency η_{xd}^{tr} of the same truck with an open differential in the drive axle is up to 8% during the first 8...10 sec (see Fig.5).

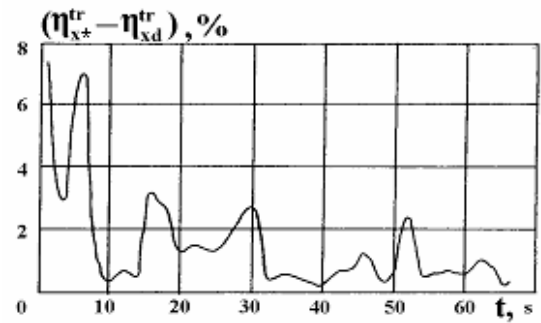


Fig. 5. Running gear efficiency of the truck

The reason for such a big difference $(\eta_{x*}^{tr} - \eta_{xd}^{tr})$ is explained in Fig. 6 that shows the ratio of the bigger tire slip, $s_{\delta dl}^{(r)}$ to the smaller tire slip, $s_{\delta ds}^{(r)}$ when the differential is open. The mean of the ratio in Fig. 6 is $(s_{\delta dl}^{(r)} / s_{\delta ds}^{(r)})_{mean} = 2.16$.

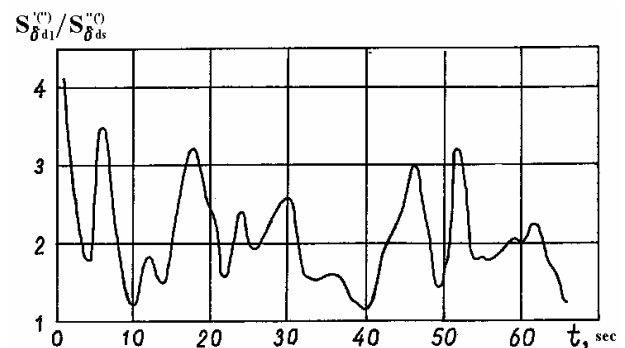


Fig. 6. The ratio of the tire slips when the differential is open

From Fig. 5 and 6, the difference $(\eta_{x*}^{tr} - \eta_{xd}^{tr}) = 0.5...1.2\%$ when the ratio $s_{\delta dl}^{(r)} / s_{\delta ds}^{(r)} = 1.5$. However, when the ratio $s_{\delta dl}^{(r)} / s_{\delta ds}^{(r)} = 1.35...1.4$, the difference in efficiency $(\eta_{x*}^{tr} - \eta_{xd}^{tr})$ gains only 0.4...0.45%. This observation is important for the further discussion.

During the implementation of Principles 1 to 4 to improve the truck performance, a decision was made on designing a mechatronic system that combines a lockable differential with a brake-based traction control system. For such a combined system, two of many engineering problems that came with that analysis were: (a) which subsystem, the lockable differential or the brake-based traction control, should operate first when the truck accelerates in a straight line motion from rest to the given speed in conditions different for the right and

left wheels and (b) when the traction control operates, to what degree a spinning wheel should be braked.

It was proven (a) that the truck displays its best performance if the differential is locked during the first 8...10 sec of motion and (b) the brake-based traction control system should act on a spinning wheel until the better wheel exerts the optimal circumferential force that results for the optimal power distributions.

As an addition to improving the truck running gear efficiency in the first stage of motion (see a recommendation in the item (a) above), the use of the lockable differential instead of the traction control also reduces both the wear of the brakes and the engine load.

For illustrating the item's (b) recommendation, Fig. 7 uses two slip curves for the drive wheels. When the differential is open, the drive wheels develop equal circumferential forces, $F'_{xd} = F''_{xd}$ and the tire slips are different, $s'_{\delta d} \neq s''_{\delta d}$. Then the traction control operates up to a moment when the wheel in better road conditions develops a circumferential force, F_x^{tr} , equal to the optimal force, F_x^{**} that was determined from optimal power distributions to the drive wheels.

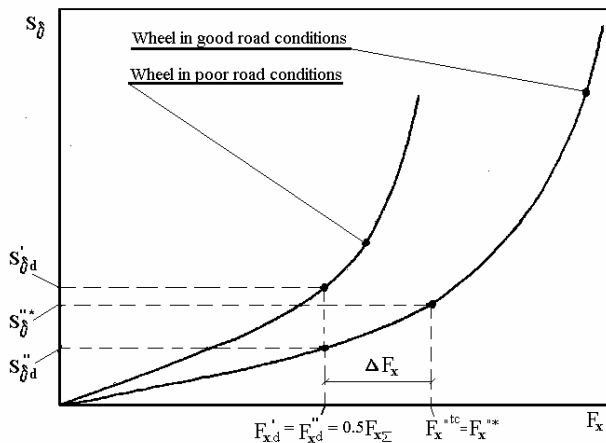


Fig. 7. Strategy for traction control operation

If the traction control system operates according to the above-proposed strategy, the mean ratio of the bigger tire slip, $s_{\delta l}^{(tr)}$ to the smaller tire slip, $s_{\delta s}^{(tr)}$ is 1.38 (see Fig.8 and compare with the value of 2.16 with the open differential). Based on this data, a reset threshold ratio $[s_{\delta l}^{(tr)} / s_{\delta s}^{(tr)}]$ at which the traction control starts operating brakes was recommended in the range of 1.35...1.40. Such preset threshold does not have a detrimental effect on the running gear efficiency of the truck (see the above-given analysis of Fig. 5 and 6) and also prevents the wear of the brake mechanisms. As proven, the mean of the specific friction work in a brake mechanism was of 0.20 kJ/cm² only. The described analysis and recommendations became components in an adaptive

control algorithm for parallel controlling the truck's lockable differential, the brake-based traction control, and the engine feeding process.

The developed algorithm can be called an adaptive one because the optimal distributions of power to the drive wheels determined in probabilistic road/terrain conditions are also a basis for setting up data needed for estimating the change in friction coefficient. This will not be addressed in this paper.

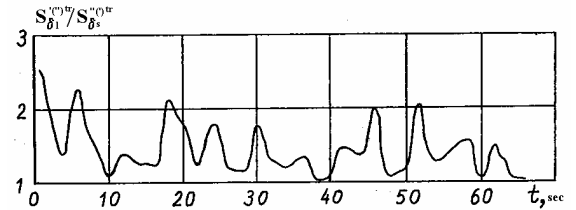


Fig. 8. The ratio of the tire slips with traction control in operation

CONCLUSION

The four principles in driveline system design discussed in the paper present a new methodology in this engineering field. The principles include the following major key-points:

- Inverse vehicle dynamics approach to determining the total power required for the vehicle motion and for the wheel power optimization
- Wheel power optimization also based on criteria of vehicle operational properties
- Synthesis of optimal characteristics for vehicle PDUs and
- Design of a driveline system that provides optimal distributions of power to the drive wheels and the best vehicle performance.

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