

A Central Differential Gear Ratio Optimization of a 6×6 Articulated Dump Truck

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ABSTRACT

This paper starts with an analysis of design configurations of the drivelines with different power-dividing units (PDUs) of main dump truck manufacturing companies. As it follows from the analysis, improvements of articulated truck energy efficiency and reduction of fuel consumption by optimizing the power distribution to the drive wheels are still open issues. The problem is that a variety of operating and terrain conditions of dump trucks requires different wheel power distributions that cannot be provided by one set of PDUs employed in a truck.

The central PDU in the transfer case was identified as the most important PDU among the five PDUs, which plays a crucial role in the power distribution between the front axle and the rear tandem of a 6×6 articulated dump truck. The paper formulates a constraint optimization problem to minimize the tire slippage power losses by optimizing the power distribution between the drive wheels. A 3D-multi-body mathematical model of a dump truck with the 29/68 ton of the curb/fully loaded mass ratio is described to solve the optimization problem. The terrains are modelled with stochastic topographical profiles, stochastic rolling resistance and tire traction-slippage characteristics. Computational sets of optimal distributions of wheel circumferential forces/torques that correspond to the optimal wheel power splits are presented for different operating and terrain conditions with the purpose to determine optimal values of the central differential gear ratio. The paper discusses the range of changes of the optimal gear ratio in different conditions.

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INTRODUCTION: ANALYSIS OF DRIVELINE SYSTEM CONFIGURATIONS, TORQUE AND WEIGHT DISTRIBUTION

The central, or the interaxle differential that is employed in the transfer case, has been in use for decades in cars with two driving axles and multi-wheel commercial vehicles, for both highway and off-road applications [1, 2, 3, 4, 5, 6]. The interaxle differential improves fuel economy [1] and turnability [4], however it needs to be locked or biased to enhance vehicle terrain mobility [4, 7, 8]. Electronic control of the interaxle differential's on/off-lock modes engaged with the rear differential lock can improve active safety [9]. There were attempts to substitute the interaxle differential from the driveline system [10, 11]. The interaxle differential has become a considerable mechanism that improves vehicle operational properties.

Various engineering problems have been solved in articulated trucks and trucks with steered wheels related to the driveline system, interaxle differential and other systems. Braking performance [12, 13], engine emission performance [14], suspension design [15],

obstacle avoidance [16], coupled dynamics of 6×6 trucks' driveline and suspension systems that impact mobility and energy efficiency [17], articulated steering design [18, 19, 20] and many other topics have been successfully treated and are still on the research and engineering agenda.

There are different types of driveline systems that are employed in 3-axle dump trucks with front steering wheels and articulated trucks [4]. However, the following three main driveline layouts are usually utilized in articulated dump trucks. Two of the drivelines provide 6×6 full-time driveline configurations and the third driveline layout has a capability to switch from a 6×4 configuration to 6×6 and back by connecting and disconnecting one of the three drive axles. Usually, the rear axle is a part-time drive axle.

The first layout shown in Fig. 1a includes five PDUs employed in the transfer case (#1), in the interaxle PDU of the tandem (#2) and three PDUs in the drive axles (## 3, 4 and 5). The second layout has a PDU in the transfer case that splits power between the front axle and the tandem's PDU between the side reduction gears of the frontward and

rearward rear axles (Fig. 1b). This driveline layout also has five PDUs, but #4 is between the left wheels and #5 is between the right wheels of the tandem. These two PDUs provide positive engagement of the wheels at each side, i.e. the two left wheels rotate with the same angular velocity and the right wheels also rotate with the same angular velocity. However, the two velocities may be different (this depends of the characteristic of PDU #2). The third layout has the capability to disconnect the third axle (Fig. 1c).

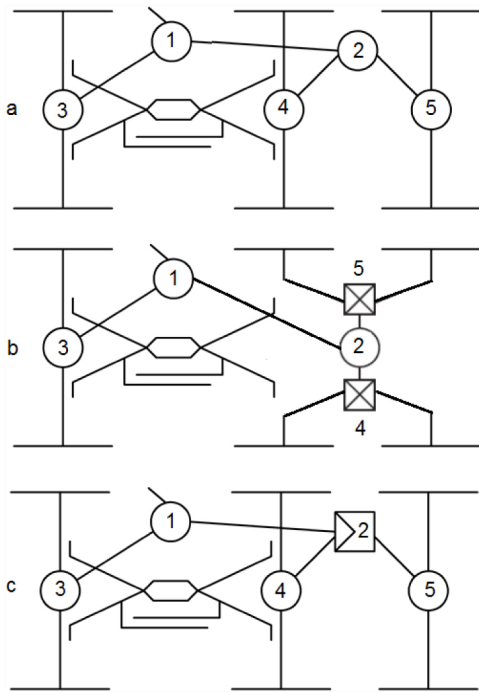


Figure 1. Main driveline system layouts of articulated dump trucks

As an analysis revealed, major manufacturing companies use different mechanisms and systems in the five power-dividing units of their trucks. Table 1 presents data and results of the analysis of 21 models of articulated dump truck produced by six companies. The table gives descriptions of the five PDUs (#1 through #5) used in the drivelines. As seen, five out of six companies go with transfer cases equipped with interaxle asymmetric differentials. One company employs an interaxle symmetric differential in the transfer case.

Asymmetric differentials are characterized the differential gear ratio, u_d , that is greater than unity

$$u_d = \frac{T_{2,3}}{T_1} > 1 \quad (1)$$

here T_1 and $T_{2,3}$ are the differential's output torques, which go to the front wheels and the tandem of the second and third axles.

Three companies (numbers 1, 3 and 5) explicitly give the value of the gear ratio of $u_d = 2$. Another two companies (2 and 4 that are marked with *) do not provide the gear ratio's values in their technical brochures, but the word descriptions of the interaxle differentials implicitly indicate that the interaxle differential is asymmetric.

Company 6 in Table 1 uses a symmetrical differential, $u_d = 1$. This is because the company employs the driveline 1c shown in Fig. 1. The third axle is disconnected and the transfer case differential splits power between the front axle and frontward rear axle. When the terrain conditions require the third axle to be engaged, the interaxle differential in the transfer case is locked and thus the value of its gear ratio does not impact the power distribution between the six drive axles.

Table 1 also presents the static weight distribution factor:

$$u_w = \frac{W_{2,3}}{W_1} \quad (2)$$

here, W_1 and $W_{2,3}$ are static weight loads on the front axle and the tandem of the frontward rear and rearward rear axles.

Since company 6 in Table 1 employs driveline layout 1c (see Fig. 1), in which engine power constantly goes to the front and middle axles connected with a symmetric differential, another static weight distribution factor is presented for this company's articulated dump trucks:

$$u_w = \frac{W_2}{W_1} \quad (3)$$

here, W_2 is the static weight load of the frontward rear axle.

An analysis of the interaxle differential's gear ratios and weight distribution factors given in Table 1 prompts several conclusions. Obviously, gear ratio u_d is close to u_w of the fully loaded ADTs, but the values of the differential gear ratios are far away from the weight distribution factors calculated for the empty trucks.

It can also be observed that the differential gear ratio is a proportion of the numbers of wheels that are connected by the interaxle differential: four wheels at the tandem and two wheels at the front axle (all the ADTs in Table 1 have single tire axles). This is what has been a rule in ground vehicle engineering for decades, i.e. an interaxle differential splits the input torque between its outputs in a way that can result in equal torques at a vehicle's drive axles. The logic here is to make the ratio of the supplied axle torques proportional to the axles' wheel circumferential/traction forces, which are proportional to the axle normal loads (it should be mentioned here that this approach mostly worked on firm roads; the situation on deformable terrains will be considered later in the paper).

The above-said on the wheel torque - traction/normal load distribution can be true if the normal axle loads are close to each other. However, the data in Table 1 lead to a different conclusion. For company 1 the weight distribution factors of the fully loaded trucks are 12...25% greater than the differential gear ratio. The weight load factors exceed the differential gear ratio by 1.7...20% in trucks of company 3 and 4...20% in trucks of company 5. The weight distribution factors of company 6 trucks are 8...20% greater than the equal-to-one gear ratio of their interaxle differential. Thus, the front axles of the ADTs experience a 20...25% overload with the traction due to the discrepancy in the wheel torque and normal load distribution.

The above-mentioned discrepancies affect further increases in empty trucks. The weight distribution between the front axle and the tandem of the empty trucks shown in Table 1 is in even further disproportion with the gear ratio of the interaxle differential. This disproportion results in (i) traction overloads of the tandem's wheels, which have lower normal loads, and (ii) traction underloads of the front wheels with greater normal loads.

There is still another negative consequence of the above-mentioned discrepancy between the wheel traction and normal loads. On deformable terrains, tire slippages become meaningfully different as well as tire slip power losses compared to firm surfaces. Different tire slippages lead to a drop in truck energy efficiency and extra fuel consumption. As a computational analysis of a 6×6 ADT with a payload of 40 ton revealed, a change of the interaxle differential gear ratio from 0.85 to 2.5 results in the truck transportation efficiency's increase from 49% to 52% on a firm even road with the peak friction coefficient of 0.7. On a slippery even road with the peak friction coefficient close to 0.3, the transportation efficiency changes from 41% to 46% when the interaxle differential gear ratio increases from 0.85 to 2.5. An observation can be seen from this data that the articulated dump truck demonstrates a better energy efficiency when the gear ratio, u_d , is greater than the weight distribution factor, u_w .

Table 1. Articulated Dump Trucks (ADTs)

Company #/ Driveline Layout	Payload	Weight load ratio: Empty/ Loaded	Power-Dividing Units		
			Transfer Case (# 1)	Interaxle or interside PDU in Tandem (# 2)	Drive axles or drive sides (## 3, 4, 5)
Company 1, Driveline layout 1a	23.2 ton	0.9127/ 2.2348	Interaxle differential with the gear ratio of 2; pneumatically lockable while stationary or on the move	Locking differential	Limited slip differentials
	27.3 ton	0.9248/ 2.4449			Controlled traction differentials
	32.5 ton	0.9992/ 2.3095			
	37 ton	1.0375/ 2.4130			
	41 ton	0.9141/ 2.4913			
	45.4 ton	0.9670/ 2.4083			
Company 2* Driveline layout 1a	26 ton	0.7097/ 2.0506	Wet-clutched central differential that can be fully locked "on the go" with 100% driveline locking for all axles	Wet-clutched interaxle differential that can be fully locked "on the go" with 100% driveline locking for all axles	Wet-clutched differentials that can be locked "on the go" with 100% driveline locking for all axles
	31 ton	0.7390/ 2.2138			
	36 ton	0.6531/ 1.8662			
			Fully Automatic Traction Control.	Differential lock	Differential locks

Table 1. (cont.) Articulated Dump Trucks (ADTs)

	43.5 ton	0.7062/ 1.9512	Central differential lock features an oil immersed clutch that is based on wheel speed sensor input	features an oil immersed clutch that is based on wheel speed sensor input	feature oil immersed clutches that are based on wheel speed sensor input
Company 3, Driveline layout 1a	23 ton	0.8042/ 2.1537	Asymmetrical planetary differential with the gear ratio of 2; pneumatically lockable	Symmetric differential with lock	Limited slip differential
	27 ton	0.8732/ 2.3305			Controlled traction differential
	32.5 ton	0.9340/ 2.0343			
	37 ton	1.0040/ 2.4039			
Company 4* Driveline layout 1a	28 ton	0.4606/ 1.2362	Interaxle asymmetric differential with a hydraulically actuated lock	Symmetric differential with a hydraulically actuated lock	Differential with a hydraulic lock
Company 5, Driveline layout 1b	28 ton	0.9664/ 2.0864	Interaxle asymmetric differential with the gear ratio of 2; 100% lockable	Limited slip differential with the torque bias of 2.64	PDU # 3 is a limited slip differential with the torque bias of 2.64. PDUs # 4 and # 5 are positive engagement units
	40 ton	1.0897/ 2.3961	Interaxle asymmetric differential with the gear ratio of 2; 100% lockable	Limited slip differential with the torque bias of 2.64	PDU # 3 is a limited slip differential with the torque bias of 2.64. PDUs # 4 and # 5 are positive engagement units
Company 6, Driveline layout 1c	24 ton	W2/W1 0.3725/ 1.0773 W23/W1 0.7450/ 2.1546	Symmetrical differential with gear ratio of 1; can be automatically 100% locked with a dog-clutch	Automatic engagement of the third axle with a dog-clutch when the transfer case's symmetrical differential is locked	Automatically 100% lockable differentials with a dog-clutch
	28 ton	W2/W1 0.4027/ 1.1678 W23/W1 0.8055/ 2.3355			
	33.5 ton	W2/W1 0.4268/ 1.1738 W23/W1 0.8535/ 2.3476			