

Axle Drive and Brake-Based Traction Control Interaction

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ABSTRACT

Brake-based traction control systems (TC), which utilize the brake of a spinning wheel of the drive axle, are widely used in passenger cars and light trucks, and recently were applied to all-wheel drive construction equipment. Such machines employ various types of interwheel drive systems (i.e., axle drives such as open differentials, limited slip differentials, etc.) to control torque split between the drive wheels and, thus, improve vehicle traction performance.

As experimental research showed, the interaction between the traction control system and the axle drive can lead to unpredictable changes in vehicle performance. Lack of analytical work in this area motivated this study of the interaction and impact of the two systems on each other and the dynamics and performance of a drive axle. The paper presents an analysis of the torque/force distribution between the driving wheels of an axle with open differential and limited slip differential with different torque bias characteristics when the traction control system is on and the driving wheels have the same/different gripping conditions. Also, the normal tire loads vary due to lateral inclination of the axle. Results of analytical research explain the nature of extra torque loads of the wheels, determine the yaw moment, and show energy losses in tires and the axle brake mechanisms. These results layout the requirements needed for the braking torque and control algorithm development of the traction control system to work “cooperatively” with limited slip differentials.

INTRODUCTION

The technical idea of the modern traction control system, most likely, came from early tank turning mechanisms. Various tanks before and during WWII used open differentials and brakes to make turns; one of the brakes was engaged to slow or stop the inner track, and thus the outer track was able to move with a higher speed. Simultaneously, the outer track developed a larger traction force that pulled the tank into the turn. However, the brake engagement resulted in heavy load on the engines; and they stalled under increased loads in many cases. For this reason, open differentials are not employed on tanks any longer.

Later, in the 1950s, two separate pedals became popular in rear axles of farm tractors with large rear tires (usually, those farm tractors did not have brakes at the front, smaller wheels). This innovation considerably improved traction of the tractors on slopes: the braking of the upper slipping wheel resulted in equal rotational speeds of the lower and upper wheels, and, in addition, the lower wheel developed a larger traction force that generated a yaw moment to prevent skidding of the tractors.

Today, many manufacturing companies employ various limited slip differentials and torque vectoring systems; wheel torque split and its influence on vehicle yaw control is at the core of research (see [1,2,3,4,5,6], etc.). Some companies claim compatibility of their limited slip differentials and brake-based TC systems when the grip conditions of the wheels (i.e., tire friction coefficients μ) are different. However, our analysis revealed that very few publications discuss the interaction of the axle differentials (open or limited) with the TC system. Some examples are as follows.

**Documents**

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A system which integrates a locking differential with TC of a heavy-duty highway truck is presented in [1]. Paper [7] discusses experimental results of the interaction of the two systems without releasing analytical work. In paper [8], a design features are considered in detail; less analytical work presented to understand the interaction of TC and limited slip differentials. Not enough attention was paid to energy efficiency/fuel consumption and yaw dynamics in technical publications.

The current study is to design a system for a 4×4 articulated loader that intelligently integrates brake-based traction control with the driveline system control. The mathematical and computer models under this study include various deterministic and stochastic data and vehicle parameters, non-linear characteristics of vehicle powertrain and chassis systems, characteristics of surface of motion, scooping material, etc. When so many systems and parameters are involved, it is hard to interpret and explain results of computer modeling and then to plan experimental research studies and validate the mathematical models and computer simulation results. For this reason, at various stages of this research project, we undertake supplementary analytical studies, which aim, firstly, to investigate and explain the physics of the interaction between two vehicle systems - the driveline system and brake-based traction control system - and, secondly, to assist with understanding and validation of computer simulations of the entire vehicle. Subsequently, the control of these two vehicle systems will be developed with better understanding the dynamics of the vehicle and its systems.

Thus, the objective of this paper is to introduce the outcomes of an analytical study that (i) analyzes the physics of torque/force split between two drive wheels connected by an open differential or limited slip differential when the TC system is applied, and then (ii) presents the influence of the tire torques/forces on the tire slip power losses (i.e., impact on vehicle energy efficiency) and yaw moment/tire lateral forces (i.e., impact on vehicle stability of motion).

DRIVE AXLE: OPEN DIFFERENTIAL AND BRAKE-BASED TC SYSTEM INTERACTION

TORQUE AND FORCE SPLIT BETWEEN DRIVING WHEELS

Consider a drive axle with an open differential and brake-based traction control system with identical road conditions under the tires (the latter means that the brakes are released).

The wheel torques are equal to one another, $T'_w = T''_w$, and the sum of the torques is the input torque (mechanical power losses in the differential are negligible [1]):

$$T'_w = T''_w; T'_w + T''_w = T_0 \quad (1)$$

It follows from this that:

$$F''_x r^{0''}_w = F'_x r^{0'}_w \quad \text{or} \quad \frac{r^{0''}_w}{r^{0'}_w} = \frac{F'_x}{F''_x} \quad (2)$$

i.e., the circumferential forces of the wheels, F''_x and F'_x are not equal if the rolling radii of wheels in the driven mode, $r^{0'}_w$ and $r^{0''}_w$, are not the same due to different normal reactions (e.g., the axle has a lateral inclination on a slope) and, sometimes, different inflation pressure values (for example, in vehicles equipped with the central inflation pressure system when one of the tires is damaged). If the difference between the radii is neglected ($r^{0'}_w = r^{0''}_w = r^0_w$), the circumferential forces are the same

$$F''_x = F'_x = \frac{T''_w}{r^{0'}_w} = \frac{T'_w}{r^{0'}_w} = \frac{T_0}{2r^0_w} \quad (3)$$

The relationship (3) applies when one of the wheels gets in poor road conditions shown in Fig. 1. Before one of the wheels gets in poor road conditions, the circumferential forces on two wheels are still equal. The wheel on poor road conditions will have higher wheel slip as shown in Figure 1 $S'_\delta \neq S''_\delta$. Here, tire slippage is defined as a measure of the difference between the theoretical V_t (in the driven mode with no torque applied) and actual V_x (in the driving mode with a drive torque applied to the wheel) linear velocities of a tire

$$S_\delta = \frac{V_t - V_x}{V_t} \quad (4)$$

Now, the brake of the wheel, which is in poor gripping conditions, is actuated by the traction control system (as shown in Fig.2). The braking torque T_b can be considered as additional resistance to motion. Therefore, a larger input torque is required to move the axle with one of the wheels spinning. This new input torque, that should be applied to the differential case when the braking torque is generated, comes as follows:

$$T_{0n} = T_0 + T_b = T'_w + T''_w + T_b \quad (5)$$

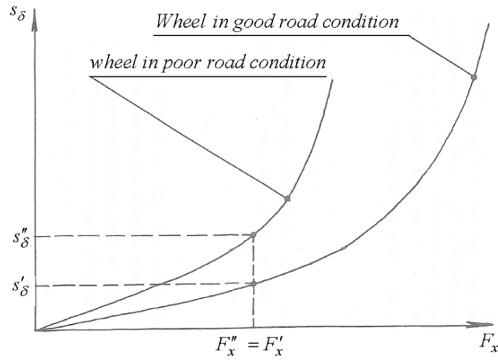


Fig. 1. Circumferential forces vs. slips of the tires (μ - curves) of a drive axle with an open differential when the right and left wheels are in different grip conditions

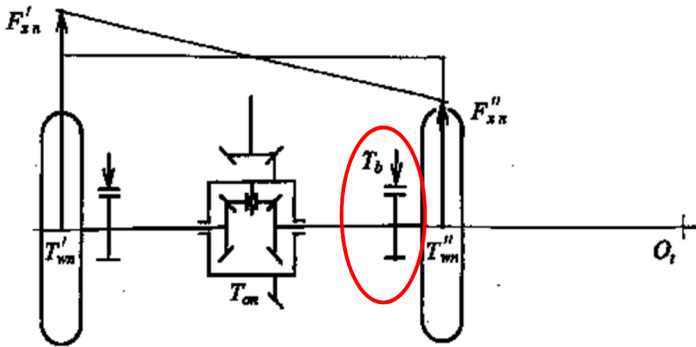


Fig. 2. Drive axle with an open differential when the right brake is actuated

The new torque T_{0n} is distributed between the driving wheels as follows:

$$T'_{wn} = 0.5T_{0n}, T''_{wn} = 0.5T_{0n} - T_b \quad (6)$$

From this one can see that the circumferential forces of the wheels are different even when the radii of the tires are the same:

$$\begin{aligned} F'_{xn} &= \frac{T_{0n}}{2r_w^0} = \frac{T_0 + T_b}{2r_w^0} = F'_x + \frac{T_b}{2r_w^0}, \\ F''_{xn} &= \frac{T_{0n}}{2r_w^0} - \frac{T_b}{r_w^0} = \frac{T_0 + T_b}{2r_w^0} - \frac{T_b}{r_w^0} = F'_x - \frac{T_b}{2r_w^0} \end{aligned} \quad (7)$$

SLIP POWER LOSSES IN TIRES

The tire slip power is the power lost due to the tire slippage, i.e. the power lost in deflecting the tire and soil in the longitudinal direction. The tire slippage as defined by (4) results in loss of the tire linear velocity

$$V_\delta = V_t - V_x = V_t s_\delta = \omega_w r_w^0 s_\delta \quad (8)$$

which leads to the slip power loss

$$P_\delta = F_x V_\delta = F_x V_t s_\delta \quad (9)$$

Therefore, the total slip power losses of the two tires of a drive axle is as follows

$$P_{\delta\Sigma} = F'_x V'_t s'_\delta + F''_x V''_t s''_\delta \quad (10)$$

As seen from (11), the slip power losses are determined by the wheel circumferential forces from (3) when the differential is open, but a brake is not applied, and from the expression (7) when a brake mechanism is applied by the traction control system. Substituting (3) and (7) in to (10) yields

• with TC off

$$P_{\delta\Sigma} = F'_x V'_t s'_\delta + F''_x V''_t s''_\delta = \frac{T_0(V'_t s'_\delta + V''_t s''_\delta)}{2r_w^0} \quad (11)$$

• with TC on

$$\begin{aligned} P_{\delta\Sigma}^{TC} &= F'_{xn} V'_{tn} s'_{\delta n} + F''_{xn} V''_{tn} s''_{\delta n} \\ &= \frac{T_0(V'_{tn} s'_{\delta n} + V''_{tn} s''_{\delta n})}{2r_w^0} + \frac{T_b(V'_{tn} s'_{\delta n} - V''_{tn} s''_{\delta n})}{2r_w^0} \end{aligned} \quad (12)$$

TC equalizes the rotational speeds of the two wheels: $\omega'_w = \omega''_w = \omega_0$. This, when taken into account the assumption on equal radii ($r_w^{0'} = r_w^{0''} = r_w^0$), reduces equation (12) to the following form

$$P_{\delta\Sigma}^{TC} = \frac{T_0 \omega_0}{2} (s'_{\delta n} + s''_{\delta n}) + \frac{T_b \omega_0}{2} (s'_{\delta n} - s''_{\delta n}) \quad (13)$$

Continued analysis of equations (7) and (13): by increasing the braking torque, T_b , the circumferential forces at the wheels can be changed to the new values, F'_{xn} and F''_{xn} , which provide new equal tire slips, $s'_{\delta n} = s''_{\delta n}$ shown in Fig. 3. In this case, the difference in slippages, $(s'_{\delta n} - s''_{\delta n})$, becomes zero, and equation (13) comes as follows:

$$P_{\delta\Sigma}^{TC} = \frac{T_0 \omega_0}{2} (s'_{\delta n} + s''_{\delta n}) \quad (14)$$