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Traction Performance Simulation of a Pushed/Pulled Driven Wheel

A. Osetinsky [1] and I. Shmulevich[2]

ABSTRACT

The existing models for prediction of traction performance of a single driven wheel should be modified to consider the load transfer effect, in order to optimize the operating performance of vehicles. A model was developed in order to predict traction performance of a driven wheel, affected by the load transfer. Traction performance of a front and a rear driven wheel, in driving and braking modes, is changed due to a pushed/pulled force acting on the driven wheel. These changes were shown using a previous study, for actual operating conditions. Simulations show significant difference between the traction performances of front and rear driven wheels of a vehicle, due to load transfer. In the driving mode, the rear driven wheel develops a net traction force greater than that of the front wheel. On the other hand, in the braking mode the front driven wheel develops a braking force significantly greater than that of the rear driven wheel. The suggested simulation algorithm may improve the prediction of driven wheel performance.

KEYWORDS. Driven wheel, Net traction, Gross traction, Off-road, Soil, Slip, Moment, Load transfer, Braking mode, Driving mode.

INTRODUCTION

An external implement or an internal interaction between driven axles of a 4WD vehicle could affect the performance of each driven wheel in the vehicle. The main reason for this change is the fact that the vertical load acting on a moving wheel is changed dynamically due to load transfer. Moreover, it can also be changed due to terrain variation. Wheel properties and soil conditions affect traction performance differently, and cause the wheel to behave differently in driving or braking modes. In order to optimize the operating performance of the vehicle, the models predicting the traction performance of a single driven wheel, should be modified to consider the load transfer effect caused by the different wheels.

There are various approaches to analyze traction performance of a vehicle with respect to the load transfer effect. Some of them are based on multi-body dynamic analysis of a moving vehicle (Crolla and Schwanghart, 1992) or modeling with commercial CAD programs such as DADS or ADAMS. These programs require a large amount of computing resources and have difficulties in evaluating the soil and the tire dynamic parameters.

Researchers such as Khalid and Smith (1981), Yu and Kushwaha (1994) studied the traction performance on the scaled models of 4WD tractors in order to derive experimentally the influence of load transfer. Zhang and Chancellor (1989), Clark and Van de Linde (1993) and Clark (1984), studied traction performance on full-sized tractors considering the load transfer effect. It is difficult to establish general conclusions from the above mentioned studies based on specific empirical data.

Other researchers developed models to predict vehicle traction performance with respect to the load transfer effect based on well-known models for a single wheel. Muro (1997) developed an analytical model for a 4WD rigid-wheel vehicle, based on a semi-empirical model, proposed by

[1] Graduate student, Faculty of Agricultural engineering, Technion – Israel Institute of Technology, Haifa, ISRAEL, agroset@techunix.technion.ac.il.

[2] Associate Professor, Faculty of Agricultural engineering, Technion – Israel Institute of Technology, Haifa, ISRAEL, agshmilo@techunix.technion.ac.il.

Bekker (1960). The vehicle traction predicted by Komandi (1978), Kotzabassis and Stout (1989) are based on an empirical approach derived by Wismer and Luth (1973). These models predict the traction performance for the driving mode only and do not cover the braking mode.

A previous paper by Osetinsky and Shmulevich (2002) presents a semi-empirical model for predicting performance of a driven wheel in a pushed/pulled condition. This model assumes that the wheel-soil contact surface can be represented in parabolic form in the longitudinal direction with the vertex in the rear point of the contact surface. It allows for a simpler analytical model, which enables a closed form solution of the wheel-soil interaction. The rut formation under the moving wheel is based on the well-known approach by Bekker (1960). The vertical ground pressure is assumed to be equal to the unit vertical load caused by the elastic deformations of the tire. The model was verified by experimental data reported in the literature. Simulations for this condition demonstrate that pushing or pulling the driven wheel substantially affects its traction performance.

The present paper will analyze the traction performance of a driven wheel in a pushed/pulled condition, using the above-mentioned model. The work will demonstrate by simulation how the load transfer will affect the traction performances. The suggested model may provide a more efficient prediction of vehicle performance and improve modern off-road vehicle design.

TRACTION PERFORMANCE OF A DRIVEN WHEEL

Traction performance of the driven pneumatic wheel was simulated according to a model suggested by Osetinsky and Shmulevich (2002), applied to a driven tire 9.5-16R-1 loaded by a vertical load of *4.0 kN*. The width b and diameter D of the tire as well as the soil properties – cohesive and frictional modules of deformation k_c, k_ϕ, exponent of deformation n, cohesion c, angle of internal friction ϕ and shear deformation modulus K – are specified by Thangavadivelu (1994). Carcass stiffness K_c and inflation pressure dependence ΔK_p of the tire are equal to the values, reported by Lines and Murphy (1991), for an inflation pressure of *1.5 bar*. The operating conditions used for the simulations are presented in Table 1 and Fig. 1 shows simulations of the traction performance of the above-mentioned driven wheel versus slip s.

Table 1. Soil properties and wheel specifications used for the simulations

9.5-16R-1 tire specifications				Soil properties					
ΔK_p	K_c	b	D	k_c	k_ϕ	n	c	ϕ	K
kN/m/bar	*kN/m*	*mm*	*mm*	$N/cm^{(n+1)}$	$N/cm^{(n+2)}$	-	*kPa*	*deg*	*mm*
134	86	240	850	2.1	4.70	1.4	6.3	18.3	8.0

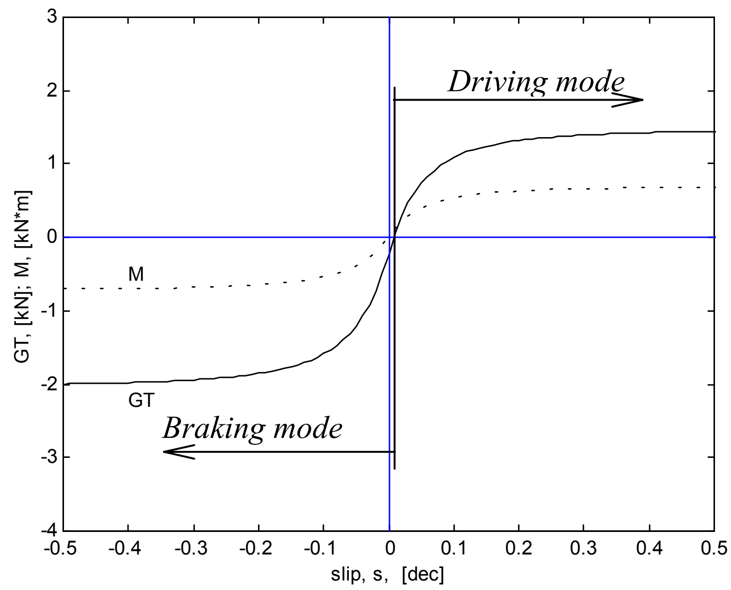

Fig. 1. Traction performance of a driven wheel ($W_{static} = 4.0\ kN$).

The gross traction force *GT* is presented by a solid line; and dotted line depicts the driving moment *M*. The right-hand side of the plot presents the traction performance in the driving mode, whereas the braking wheel traction performance is shown on the left-hand side.

It can be seen that the traction performance is not behaving symmetrically throughout the two modes. The force required to move the braking wheel is greater than the force developed by the wheel in the driving mode. Since the vertical load acting on the moving wheel affects the traction performance, an increase of the load on the wheel magnifies the gross traction force and the moment. On the other hand, reduction of the vertical load decreases the performance values. The gross traction force vs. slip, caused by different vertical loads is shown in Fig. 2.

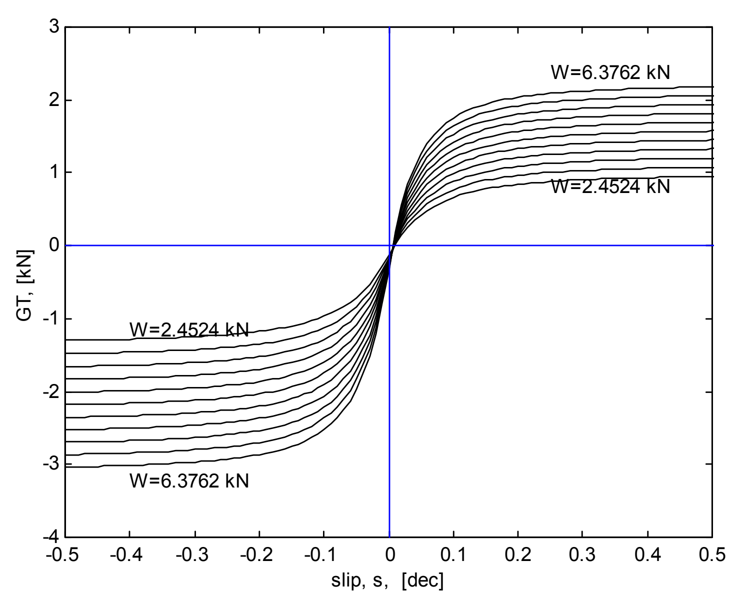

Fig. 2. Gross traction force of a driven wheel for various vertical loads.

The vertical load applied to the driven wheel varies between *2.45* to *6.38 kN*. One can see that in the cluster of curves the value of gross traction force increases in proportion to the vertical load. In the braking mode, the gross traction force has a negative value. The above-mentioned changes of the vertical load produce the maximum values of gross traction force ranging from *0.98 kN* to

2.21 kN in the driving mode. In the braking mode a maximum gross traction force (braking force) of *-1.34 kN* to *-3.10 kN* is achieved respectively.

The model predicts an intersection of lines of traction performance with the axis of slip at the same point. This point indicates the boundary value of slip between driving and braking modes. As can be concluded from the simulation results, the braking force reached in the braking mode is *30%* to *40%* more than the gross traction force developed by the wheel in the driving mode.

EFFECT OF LOAD TRANSFER ON TRACTION PERFORMANCE OF A WHEEL

The vertical loads on the wheels of a moving vehicle change dynamically during operation due to load transfer. The load transfer is the change between the dynamic and static loads acting on the wheel, due to external forces, soil variation or acceleration/deceleration of the vehicle. In order to predict the traction performance of a wheel affected by load transfer, the variations of the vertical load on the wheel should be considered. The dynamic load can be found from equations of equilibrium of the moving wheel. Geometrical dimensions of the vehicle affect the equilibrium of the wheels. The load transfer changes the equilibrium of the front and the rear wheels in different ways.

There are four possible combinations of driven wheel operation: front and rear wheel in driving and braking modes (Fig. 3a–d). The total weight of the vehicle W distributes statically in a certain way between the front and rear wheels. The moment M applied to the driven wheel causes an equivalent moment of reaction applied to the chassis. This results in dynamic variations of the static vertical load on the wheel by the respective value.

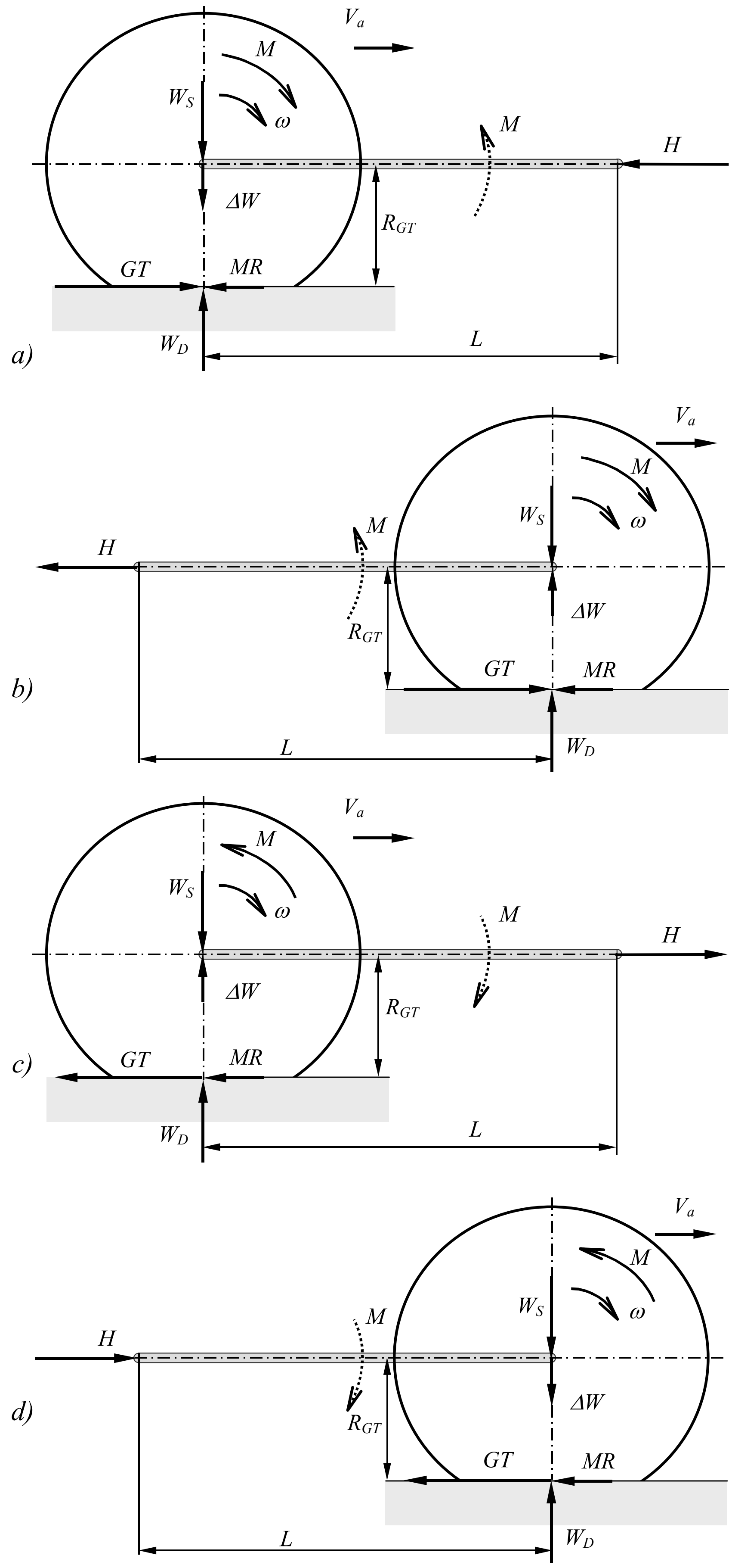

Fig. 3. Influence of load transfer on a driven wheel: a) rear wheel in driving mode; b) front wheel in driving mode; c) rear pulled wheel; d) front pushed wheel.

In driving mode, the power input is the torque M applied on the wheel, which results in the gross traction force GT at a distance R_{GT} in relation to the center of the wheel. The gross traction force GT is equivalent to the sum of the resisting forces MR and the required net traction force H (Fig. 3a, b).

In the braking mode, the power input is the pushed/pulled force applied to the axle of the wheel, which cause the moment of resistance M on the wheel; and the gross traction force GT transforms into additional resistance force (Fig. 3c, d).

The driving moment applied to the wheel is associated with the gross traction force as follows:

$$M = GT \cdot R_{GT} + M_r \tag{1}$$

where M – driving moment on the wheel, [kNm]; M_r – moment due to eccentricity of the vertical component of the soil reaction, [kNm]; GT – gross traction force, [kN]; and R_{GT} – distance of application of the gross traction force in relation to the center of the wheel, [m].

The driving moment, acting on the front wheel, and the pull force applied to the rear one causes a dynamic reduction of the vertical load acting on the wheel by value ΔW (Fig. 3b, c). The inverse situation is observed when the driving moment is applied to the rear wheel, or when the push force acts on the front wheel (Fig. 3a, d). This causes the vertical load on the wheel to dynamically increase. Dynamic variation of the vertical load on the driven wheel can be calculated as:

$$W_D = W_S + \Delta W \tag{2}$$

$$\Delta W = \frac{M}{L} \tag{3}$$

where W_D , W_S – dynamic and static vertical loads on the wheel, [kN]; ΔW – dynamic variation of the vertical load [kN]; M – driving moment on the wheel, [$kN \cdot m$]; and L – distance from center of wheel to drawbar hitch point [m].

Dynamic variation of the vertical load on the wheel has different effects on front and rear driven wheels. As mentioned before, a curve of the traction performance, taking into consideration the load transfer, can be derived on the basis of the traction performance curves for various vertical loads acting on the moving wheel (Fig. 2). The traction performance is simulated using a model developed by Osetinsky and Shmulevich (2002).

Fig. 4a–d shows the effect of the load transfer on the gross traction performance in the conditions described by Fig. 3a–d. The driving mode is schematically presented in Fig. 4a, b. The bold line shows the traction performance for a certain static vertical load W_S applied to the wheel and kept at a constant value. According to this line, each value of the gross traction forces GT_1, GT_2, GT_3, GT_4 can be reached at the corresponding values of slip: s_{1S}, s_{2S}, s_{3S}, s_{4S}.

The behavior of the driven wheel is different when the vertical load varies. The applied torque proportionally increases the vertical load on the rear wheel in the driving mode. The traction performance of the wheel should fulfill equation (3). For the rear driving wheel one assumes that the required value of gross traction force is GT_1 (Fig. 4a). The corresponding torque M_1 dynamically increases the vertical load on the wheel to the value W_1. This value is greater than the static value W_S by ΔW_1 :

$$W_1 = W_S + \Delta W_1 \tag{4}$$

Thus, the traction performance of the wheel is described by a thin dashed line, which refers to the actual vertical load W_1. According to the simulation model, a new value of actual slip, s_{1R}, was derived from the gross traction force GT_1 and vertical load W_1 (Fig. 4a). Similarly, one can calculate the actual slip for any arbitrary value of gross traction force with the load transfer correction. The following actual values of slip s_{2R}, s_{3R}, s_{4R} were found for the above-mentioned values of traction force (GT_2, GT_3, GT_4 respectively). Using these corrected points, a line of actual traction performance for the rear driving wheel, loaded by the static weight W_S, can be plotted (thick dashed line in Fig. 4a).

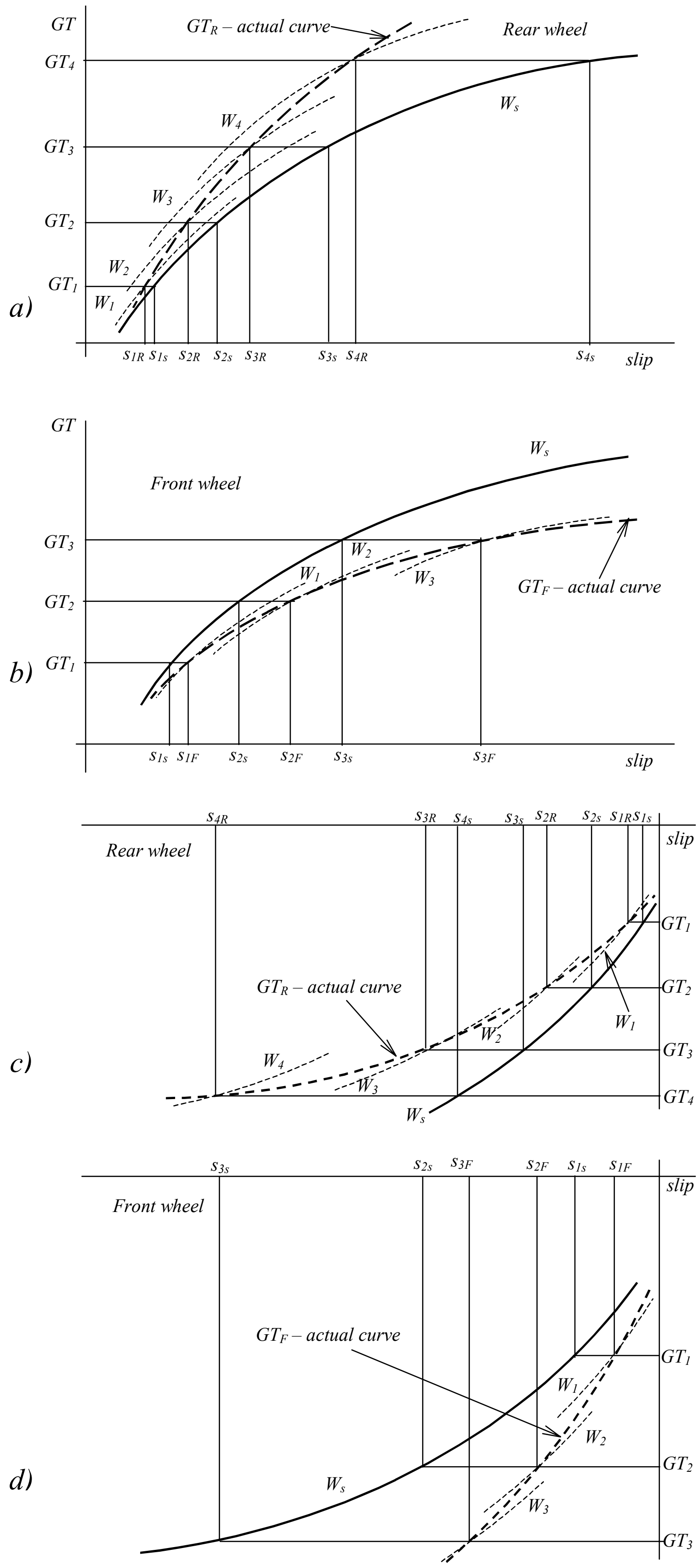

Fig. 4. Traction performance of a driven wheel affected by load transfer: a) rear wheel in driving mode; b) front wheel in driving mode; c) rear pulled wheel; d) front pushed wheel.

The applied driving moment proportionally decreases the vertical load on the front wheel in the driving mode. In the same way, the line of the actual traction performance for the front driving wheel can be derived (Fig. 4b). It can be seen that the actual curve of traction performance of the rear driving wheel lies above the proposed line for static load. When the same wheel operates as a front wheel, the actual line of the traction performance lies below the proposed line for static load. Thus, a rear driving wheel yields the same value of gross traction force at a lower slip than the front one.

The traction performance of the braking wheel is analyzed using the same method that was applied to the driving wheel. The load transfer affects the traction performance of the wheel in the opposite way: the vertical load increases on the front wheel and decreases on the rear one. Therefore, the actual line of traction performance lies above the curve for a constant (static) vertical load acting on the rear wheel, whereas for the front wheel it lies below. This means that for the same slip, the value of gross traction force (braking resistance) of the front wheel is higher than the one for the rear wheel (Fig. 4c, d).

TRACTION PERFORMANCE SIMULATIONS OF A FRONT/REAR DRIVEN WHEEL

In order to simulate the behavior of a driven wheel, affected by load transfer, the equilibrium equations (1)–(3) were applied to the modeled traction performance. A program using Matlab software was written to enable the simultaneous solution of these equations using iteration method. Simulations were carried out for the wheel and operating conditions shown in Table 1. The distance *L* from the center of the wheel to drawbar hitch point is equal to *0.69 m*.

Simulations of traction performance of a driven wheel are presented in Figs. 5–8. The solid line shows the performance of the wheel operating under a static vertical load of *4.0 kN*. The dotted lines indicate traction performances of driven wheel operating under various vertical loads.

The traction performance of a rear driven wheel is marked by hollow circles (o). Plus signs (+) refer to a front driven wheel. In order to demonstrate the influence of load transfer, traction performance of a driven wheel operating under a constant vertical load was chosen as a reference value. A thin line presents this performance.

Dynamic changes of the vertical load acting on front and rear driven wheels differ from the static load through all the values of slip (Fig. 5).

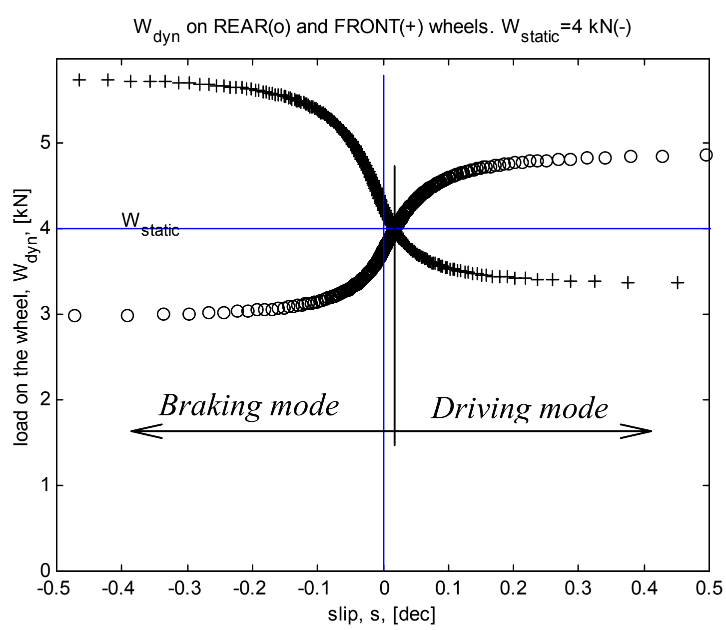

Fig. 5. Simulations of vertical load on the driven wheel vs. slip.

In the driving mode the vertical load on the front wheel decreases, whereas on the rear one it increases with the growth of slip values. The opposite effect occurs in the braking mode. The vertical load acting on the pushed front driven wheel, due to load transfer, increases significantly, whereas it decreases on the pulled rear driven wheel. The intersection point of the lines representing the vertical load on the wheel (front and rear one) indicates a stationary wheel and the corresponding vertical load is equal to the static load *4.0 kN*.

Fig. 6 shows the influence of the load transfer on motion resistance. It is well known that the vertical load on the wheel directly affects the motion resistance. Therefore, the performance of motion resistance changes in a similar way to the vertical load as shown in Fig. 5. One can see that a significant growth of motion resistance above the static value occurs for the pushed front driven wheel. The motion resistance of the rear wheel and the front wheel is a little larger and a little smaller, respectively, than the static value. A dot-dashed line in Figs. 7–8 represents the value of motion resistance of the driven wheel operating under the static vertical load of *4.0 kN*.

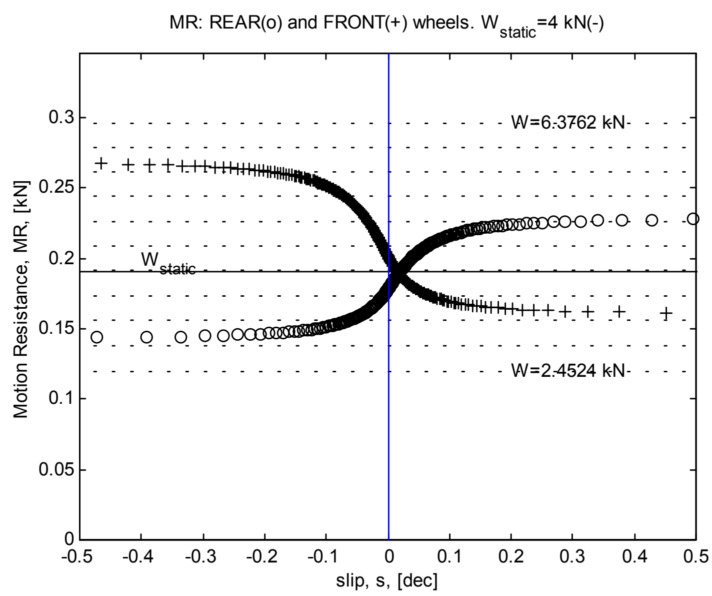

Fig. 6. Motion resistance simulations of front and rear driven wheels.

Fig. 7 shows gross traction force simulations. Traction performances of the rear and front driven wheels differ from the reference curve, calculated without load transfer. The line representing the rear wheel lies above the reference curve and the traction performance of the front wheel is below it. There is only one common point for these three curves – the point of zero gross traction force. A significant deviation from the reference line is observed for the front pushed wheel. The braking force of the front driven wheel is about two times higher than the braking force of the same rear driven wheel. A similar performance is predicted for the driving moment.

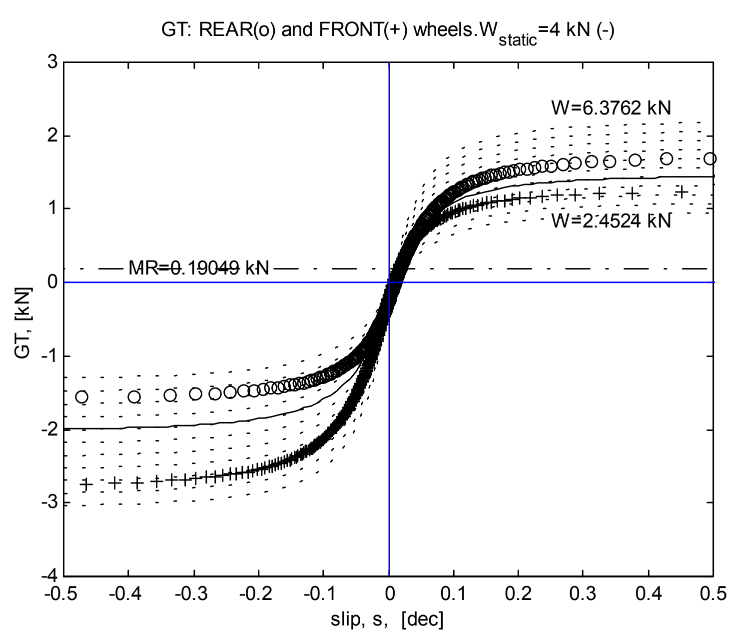

Fig. 7. Gross traction force simulations of front and rear driven wheels

The net traction force, presented in Fig. 8, is calculated by subtraction of motion resistance from the gross traction force. In the braking mode the net traction is equal to a force, which is required to move the wheel: i.e. to pull the rear or push the front one. One can see that in the driving mode a rear driven wheel develops a net traction force greater than that developed by the front wheel. In contrast, in the braking mode the braking force of a front pushed driven wheel is significantly greater than the braking force of a rear pulled driven wheel.

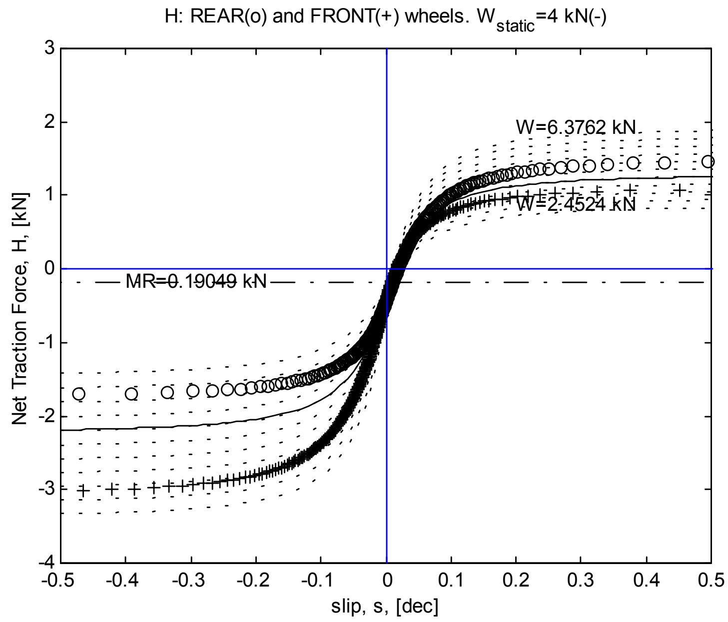

Fig. 8. Net traction force simulations of front and rear driven wheels.

As can be seen, the rear driven wheel develops higher traction in the driving mode in comparison to the front wheel and the front driven wheel develops significantly higher braking force as compared to the rear one. These results demonstrate quantitatively the known phenomenon of load transfer in a vehicle.

Simulations of the traction performance of a front pushed or rear pulled driven wheel show that the proposed method can improve prediction of traction performance of the vehicle. This method could be especially useful in the design of multi-drive vehicles.

CONCLUSIONS

1. A model for prediction of the traction performance of a driven wheel considering load transfer was developed.

2. The traction performance of a front and rear driven wheel, in driving and braking modes, was simulated for operating conditions found in literature.

3. The simulations demonstrate quantitatively significant differences between the traction performances of front and rear driven wheels due to load transfer.

4. In driving mode a rear driven wheel develops a net traction force greater than that developed by a front driven wheel in the same operating conditions. On the other hand, in braking mode the front driven pushed wheel develops a braking force significantly greater than that of the rear driven wheel.

5. The results show that the proposed method can improve prediction of traction performance of multi-drive vehicles.

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