THE NEED OF PROPER MODELING OF TRACTION CONTROL SYSTEM IN MOBILITY SIMULATIONS WITH SOFT SOIL

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ABSTRACT

When building simulation models of military vehicles for mobility analysis over deformable terrain, the powertrain details are often ignored. This is of interest for electric and hybrid-electric vehicles where the maximum torque is produced at low speeds. It is easy to end up with the drive wheels spinning and reducing traction and eventually the vehicle digging itself down in the soil.

This paper reveals improvements to mobility results using Traction Control Systems for both wheeled and tracked vehicles. Simulations are performed on hard ground and two types of deformable soil, Lethe sand and snow. For each soft soil, simulations have been performed with a simple terramechanics model (ST) based on Bekker-Wong models and complex terramechanics (CT) using the EDEM discrete element soil model which Pratt & Miller Engineering (PME) has been instrumental in developing.

To model the traction control system a PD controller is used that tries to limit the slip velocity at low speed and wheel slip at higher velocity. Controlling the slip velocity, i.e. the relative tangential velocity between the wheel and ground, or track and ground is usually best for low speed. A typical preset value would be in the range of 50 – 100 mm/s depending on the usage scenario. Using relative slip velocity also avoids a division by zero at low speeds or at wheel lock-up. The lower value is used mainly for crawl mode, when trying to get unstuck after being dug down deep into the soil. Based on the optimal pre-set values for slip or slip velocity, a correction factor is applied to the throttle to limit the slip or slip velocity.

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1. INTRODUCTION

Though multi-body simulations (MBS) have been around and a standard tool in development and analysis for several decades, the interactions with soft soil is a relatively new development made possible through improvements in numerical methods and computer speeds.

Soft soil interaction simulations can be divided in two distinct categories; Parametric models and discrete element models (DEM). Parametric models are by far still the most common, with soil models described by a limited number of parameters. The most common model was developed by Bekker [1] and continued by Wong [2][3]. With some extensions it can handle vertical loading and unloading, shear forces between material and soil as well as internal to the material. Later extensions also handle bulldozing effects. These models are implemented to some extent in all commercial MBS software including ADAMS/Tire and ADAMS/Tracked Vehicle that has been used in this paper.

More modern approaches usually interface the MBS model with a DEM model. DEM models try to replicate the individual soil particles and are therefore by nature much more time consuming. Available computer resources usually set a lower limit for the size of the particles that can be used. In this paper, EDEM from DEM Solutions Inc. has been used coupled with ADAMS.

The background for this paper is twofold: 1. For most mobility simulations for development or verification of military vehicle, simulations are usually run on hard ground where the only significant number is the available torque. This method is established and are carried over to the soft soil simulations. 2. With increasing popularity of hybrid and electric drive vehicles, the maximum torque is delivered at low speed which makes it significantly easier for any existing driver model to spin the wheels and reduce the traction. This is valid on all ground types.

2. TRACTION CONTROL MODEL

To implement the traction control system, a pure throttle reduction-only system was used. A simple model, with only two parameters to tune.

The longitudinal slip of the tire can be defined as

$$s = \frac{r\omega - V_x}{V_x}$$

Where r is the effective rolling radius, ω is the rotational velocity of the tire and V_x the longitudinal velocity of the vehicle. As dividing with the velocity is a bad idea, this is rewritten as

$$V_{slip} = sV_x = r\omega - V_x$$

It is also well known that it is only useful to control the slip-velocity to this expression at higher speeds. Therefore, at lower speeds, a minimal tangential velocity V_{min} is used as a parameter. This leads to the final expression for the optimal slip velocity as

$$V_{Opt} = MAX\{V_{min}, V_{slip,Opt}\}$$

For most cases, V_{min} is set to 100 mm/s and $S_{Opt}S_{Opt}$ to 10%. S_{Opt} is taken to be the peak of the longitudinal friction curve which is close to 10% for most larger tires. $V_{Slip,Opt}$ = 100 mm/s is derived over years of simulation and tuning and might not be optimal for all tires, but works well. This has been tuned for hard ground with low friction for example wet or light ice and produces good results on split mu surfaces. It should also be noted that this TCS system is developed for pure longitudinal slip conditions and does not correct for any lateral slip.

The slip error can now be calculated as

$$\varepsilon = 0, \quad V_{slip} < V_{Opt}$$
$$\varepsilon = V_{slip} - V_{Opt}, \quad V_{slip} > V_{Opt}$$

A simple PD controller is used for the throttle correction factor

$$K = 1 + P\varepsilon + D\dot{\varepsilon}$$

And the corrected throttle is then given by

$$T_{TCS} = {T_{Driver}}/{K}$$

Figure 1 shows how the optimal slip velocity calculates for a run on sand where the grip is not able to sustain a constant velocity. At higher speeds in the beginning, the optimal slip velocity is following the 10% value of S_{Opt} and when the velocity decreases the optimal slip velocity locks in to $V_{Slip,Opt}$ of 100 mm/s.

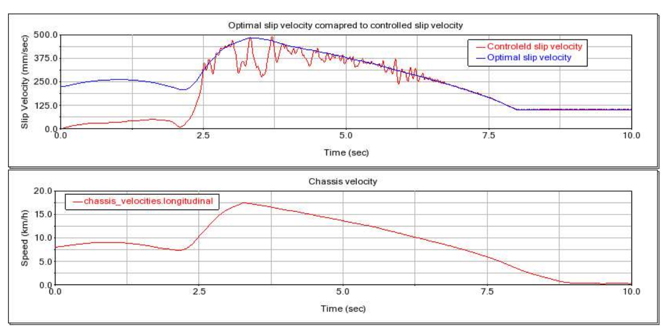

Figure 1 Optimal slip velocity and controlled slip velocity compared to vehicle velocity

3. PARAMETRIC SOIL MODELS

There are several problems with the Bekker-Wong parametric soil models when it comes to predicting traction control behavior.

The first is that the Bekker-Wong model and most implementations are of a static nature. There is no velocity component to the shear force build-up, only a displacement dependency.

Second problem is the shear model used. It partly goes together with the first point above, but also the fact that there is no drop-off off the shear forces with increased slip. The three most common models for shear forces are described here.

The first type was proposed by Janowski and Hanamoto. As can be seen there is a constant shear force once the full shear displacement is built up. This suggests that any amount of slip once high enough will produce the same shear force.

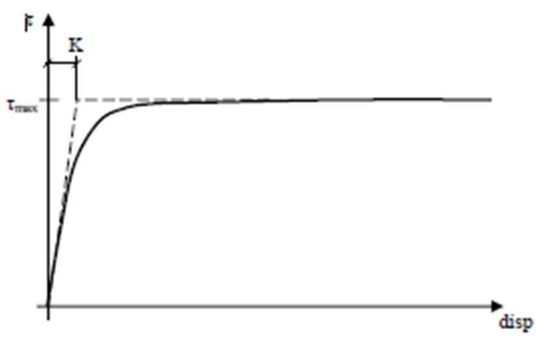

Figure 2 Shear stress vs. shear displacement type 1.

The second shear type is representative of a muskeg mat. The shear forces reach a distinct maximum before roots and other organic material is sheared apart after which the shear forces drop to zero. This model was proposed by Wong and Preston. This could in theory lend itself well to a traction control if the shear displacement could be estimated. As this is in general near to impossible, the simple traction control model used in this paper is not suitable either.

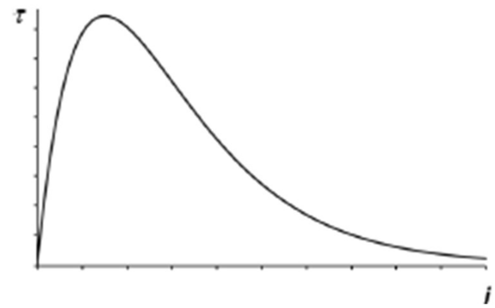

Figure 3 Shear stress vs shear displacement type 2

As a hybrid between type 1 and type 2, Pokrovski, Kacigin, Gustov and Oida proposed type 3. It has the same disadvantages as type 2 when it comes to predicting traction control interaction with the soil.

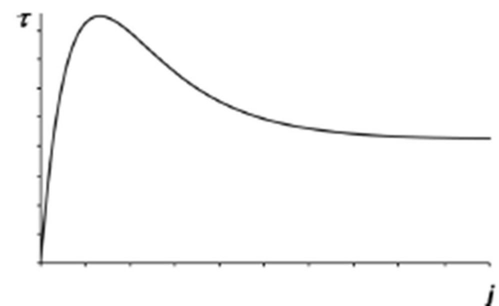

Figure 4 Shear stress vs shear displacement type 3

The third disadvantage with the parametric models is that there is no mass transport in the implementations tested here. With the inertia effects of the soil, there is an advantage of using higher slip than what this TCS implementation predicts as the acceleration of soil particles helps drive the vehicle forward. This seems to be an advantage mainly when the ground pressure is low and the sinkage is limited as is the case with tracked vehicle or high normal carrying capacity of the soil. Muskeg is a good example of this type of soil; sinkage is low, but once the shear plane is established, the horizontal movement of the soil will help the traction. On the other hand, when ground pressure is high, the wheel (or track) tends to dig itself into the soil with extensive slip.

4. COMPLEX TERRAMECHANICS MODELS

Improvement of computers and the recent advancements in affordable GPU computing has made it possible to work with discrete element models (DEM) of the soil. It is still extremely time consuming as the soil easily consists of millions of particles. Of practical use today is only gravel and coarse sand with particle size in the range of millimeters. Another quantum leap in computing power is needed to be able to have useful models of fine sand, silt and mud. Research is going on into using computational fluid models (CFD) for these extreme fine granular materials. That is not covered in this paper.

A second problem using DEM models is the correlation to the well-known parametric models where hundreds of soil properties have been measured using Bevameter equipment. Development is ongoing to be able to classify any soil built in EDEM using a built in Bevameter test rig and to provide a library of "standard" soil models according to ref [1].

The third problem is that currently the ADAMS-EDEM coupling does only support rigid tires. At Pratt & Miller, a research and development project is on-going to develop a deformable tire interface between ADAMS and EDEM. Other software already has this interface, but as ADAMS is the dominant player in the market, there is a need for this to be implemented in the ACSI protocol that is used to interface ADAMS with EDEM [5][6].

Of course, using a DEM model for the soil eliminates all the disadvantages mentioned for the parametric soil models. The particle bed is fully dynamic, supporting all dynamic effects between wheels or tracks and the soil. The mass effect of moving the soil is naturally covered.

4.1. Traction control effects on DEM roads

This is the best approach to evaluate the effects of traction control system (and ABS brake systems) for soft soil interactions. There are also cases where a TCS system is required to provide the desired traction of the vehicle and to prove the capability of the design on soft soil.

With the simple traction control model described previously, the behavior of the vehicle changes dramatically. The road used for this is a loose, non-compressible gravel with particle sizes around 12 mm in average. There is some cohesion between the particles, emulating wet conditions. The angle of repose of this material is just around 25° (46%), so it is not expected to be able to go without problems up this slope.

The vehicle used in this example is a ~20-ton, eight wheeled assault vehicle model. The front two axles are driven directly by the internal combustion engine through an automatic transmission and the gear ratios are tuned for top speed on hard surface. Axle 3 and 4 are driven by individual electric motors tuned for maximum torque in off-road conditions to provide optimal mobility. It is intended that on highway, the electric motors will not contribute at all.

The analyzed scenario is a 35% slope and the target is to maintain a constant speed or accelerate up the slope. When the vehicle enters the slope, the driver ramps up the throttle to 60% which increases the speed temporarily before all wheels enter the gravel.

Without TCS, the vehicle quickly digs in and comes to a halt which is illustrated in Figure 5

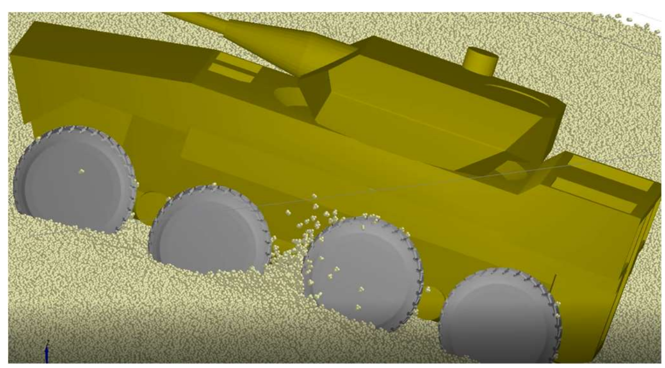

Figure 5 Vehicle on 35% slope without TCS

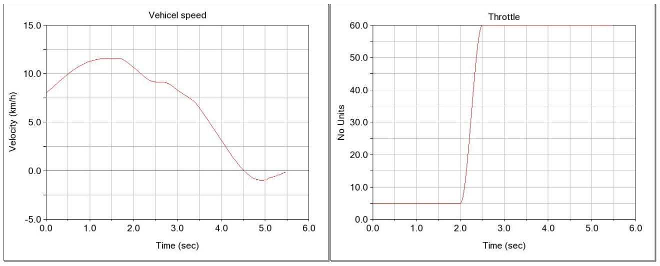

Figure 6 Vehicle speed and throttle without traction control

Using the parameters tuned for hard surface does not produce a good result either. These parameters are way to limiting on the throttle and forces the vehicle to slow down as shown in the following plots.

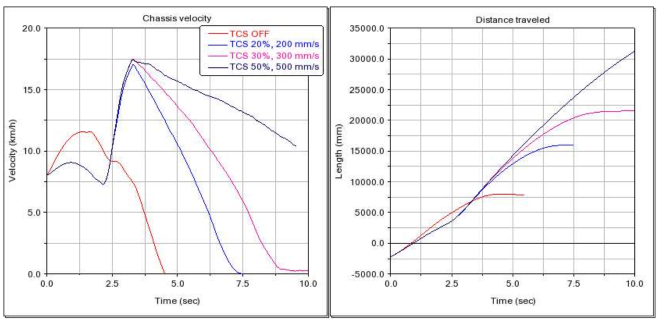

Figure 7 Velocity and distance traveled for different TCS settings

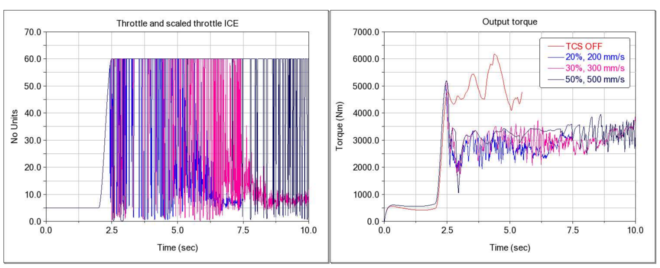

Figure 8 TCS behavior for ICE (axle 1 &2)

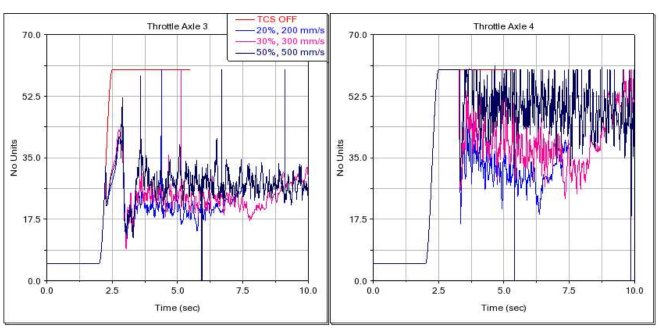

Figure 9 TCS behavior for axle 3 & 4

Figure 8 and Figure 9 need some more explanation. The TCS system for the ICE on axle 1 & 2 looks very noisy. But this is effectively filtered by the inertia of the diesel engine that reduces the variations of the TCS system to a signal that is similar in character to the electric motors on the rear 2 axles. Axle 3 torque is further restricted compared to axle 4 as the geometry of that suspension has a large up-jacking effect that reduces normal load with increased driving torque.

Utilizing higher allowed slip on axle 1 & 2 causes them to dig in, similar to what is shown in Figure 5.

Some more investigations indicate that the TCS is most important on the front two axles for this vehicle. The front two axles compress the gravel so much that the two rear axles have better grip and therefore a much higher slip limit can be allowed. Even with a very high allowed slip on axle 3, the TCS does a good job preventing the tire to “skip” over the surface.

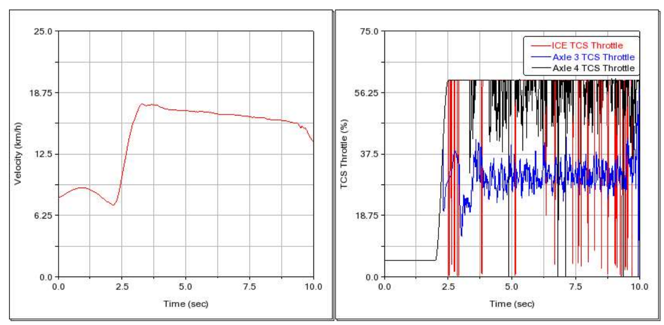

Figure 10 Optimal TCS settings

Figure 10 shows the resulting “optimal” TCS settings. The vehicle can not hold the speed perfectly but is able to almost maintain the speed which was better than expected. This setting corresponds to S_{Opt}=50% and $V_{Slip,Opt}$=500 mm/s on axle 1 and 2 (the ICE driven axles) and S_{Opt}=40% and $V_{Slip,Opt}$=1200 mm/s on axle 3 and 4. As can be seen, axle 3 is limited the most while almost all throttle is passed through to axle 4.

5. Conclusions

Parametric models like the Bekker-Wong does not accurately represent the dynamics of the soil bed. The model lacks the dynamics of the soil and mass transfer effects and the shear forces are not described as functions of slip speed. Therefore, there is no need for a traction control system to prove the performance of the vehicle or to prove the necessity of a TCS or ABS system.

DEM models are very time consuming even on fast computers. A lot of the time goes to writing results files, so utilizing a solid-state drive and using a script that sequentially moves the files to a regular drive can save 30% of the time. Utilization of a good GPU processor can speed up the simulations a factor of 12. With this setup, a good simulation can be performed in just a matter of hours which would make sue of commercial optimization software such as HEEDS very useful.

These investigations have shown that the tuning of the TCS system is very vehicle dependent and the settings that works for hard ground is not the optimal for soft soil. Currently Pratt & Miller is working on development of an adaptive TCS system that would adjust for the soil conditions and suspension layout. Utilizing load sensors in each hub would provide a very simple solution, but that is a very costly solution and therefore not realistic. A good observer model and Kalman filter seems to be the way to go for this.

1. REFERENCES

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