Considerations Regarding Vehicle Cone Index for Fine-Grained Soil

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***Abstract*—Vehicle Cone Index (*VCI*) is the most representative parameter to establish the vehicle capability to overpass the tough conditions caused by the soft soil. Its importance is emphasized by the fact that it has been recently included in TOP 02-2-619A. According to this test operations procedure, *VCI* can be both estimated and measured. Original methods – prediction with TruckSim software, as measurements in a natural fine grained soil for a 4×4 military vehicle, are presented in the study. The difficulties encountered with site selection, equipment used and test lane procedure represent truly learned lessons for all those concerned with off-road mobility. Moreover, the test results and the analysis done in this paper could be a reference for future vehicle pass simulations.**

***Index Terms*—Mobility, NRMM, simulation, soft soil, TruckSim, Vehicle Cone Index.**

I. Introduction

The Vehicle Cone Index (*VCI*) is defined as the "minimum soil strength in the critical soil layer, in terms of rating cone index for fine grained soils or in cone index for coarse grained soils, required for a specific number of passes of a vehicle, usually one pass (VCI_1) or 50 passes (VCI_{50})" by The International Society for Terrain-Vehicle Systems (ISTVS) [1]. The first researches on *VCI* were done by United States Army Engineer Waterways Experiment Station in the 1950s. There have been a number of additional tests and analyses, materialized in two aspects that show the significant role it has gained over time. The first aspect is that *VCI* has been adopted by NATO Reference Mobility Model (NRMM) [2,3] as a fundamental parameter to predict the motion resistance, the drawbar pull and the tractive force of the wheeled and tracked vehicles running on fine-grained soils (*FG*). The second aspect is that the *VCI* determination methodology appeared in 2016 as a stand-alone activity in a standardized test procedure TOP 02-2-619A [4]. This standard takes into account the estimation of *VCI* using empirical relations, as well the effective measurement of the minimum soil strength indispensable for a specific vehicle to pass once over the soil. The relationship between the two above-mentioned assessments is essential. Without *VCI* estimation, the identification of the terrain that assures the minimum rating cone index (*RCI*) for one pass would lead to many trials. TOP 02-2-619A has the merit of bringing back the experimental side as well as all the technical papers in the last years which were focused on theoretical principles. For example, Priddy made an analysis of VCI_1 modelling focusing on existing models and on new development models [5]. The same author compared the VCI_1 results based on the current NRMM relations and on Mean Maximum Pressure (*MMP*) methodology [6]. The estimation of VCI_1 for M1 Abrams and HMMWV was done by Ciobotaru in order to emphasize the behavior of tracked and wheeled vehicle on soft soils [7]. Different from the ones exemplified, the purpose of this paper is to address this topic in the spirit of TOP 02-2-619A, presenting an original way of estimating VCI_1, as well as the activities performed on a field test with the armored vehicle AJBAN 440A produced by NIMR Automotive from United Arab Emirates. Implicitly, all the results obtained in this article are founded on the technical characteristics of AJBAN 440A.

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II. VCI_1 Estimation

The VCI_1 for fine-grained soils is calculated using the formulas presented in TOP 02-2-619A and in all the previously mentioned technical papers and reports:

$$VCI_1(MI, DCF) = \begin{cases} \left(11.48 + 0.2 \cdot MI - \dfrac{39.2}{(MI + 3.74)}\right) \cdot DCF, MI \le 115 \\ \left(4.1 \cdot MI^{0.446}\right) \cdot DCF, MI > 115 \end{cases} \quad (1)$$

where:

Mobility Index (MI)

$$MI = \left(\frac{CPF \cdot WF}{TEF \cdot GF} + WLF - CF\right) \cdot EF \cdot TF \quad (2)$$

Mobility Index Factors

$$CPF = w/(0.5 \cdot n \cdot d \cdot b) \quad (3)$$

$$TEF = (10 + b)/100 \quad (4)$$

$$WLF = w/2000 \quad (5)$$

$$CF = h_c/10 \quad (6)$$

$$GF = 1 + 0.05 \cdot C_{GF} \quad (7)$$

($C_{GF} = 1$ if tire chains are used or 0 if not)

$$EF = 1 + 0.05 \cdot C_{EF} \quad (8)$$

($C_{EF} = 1$ if vehicle specific power < 10 HP/t or 0 if not)

$$TF = 1 + 0.05 \cdot C_{TF} \quad (9)$$

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$(C_{TF} = 1 \text{ if manual transmission or 0 if automatic transmission})$

$$WF = C_{WF1} \cdot \frac{w}{1000} + C_{WF2} \tag{10}$$

with:

$C_{WF1} = 0.033$ and $C_{WF2} = 1.050$, for $2000 \le w < 13500$ lbs.

A. Deflection Correction Factor (DCF):

$$DCF = \left(\frac{0.15}{\delta/h} \right)^{0.25} \tag{11}$$

where for (1)–(11): *VCI* [psi]; *CPF* – contact pressure factor; *TEF* – traction element factor; *WLF* – wheel load factor; *CF* – clearance factor; *GF* – grouser factor; *EF* – engine factor; *TF* – transmission factor; *WF* – weight factor; *w* – average axle loading [lbs.]; *n* – average number of tires per axle; *d* – average tire outside diameter (inflated; unloaded) [in]; *b* – average tire section width (inflated; unloaded) [in]; h_c – vehicle minimum clearance height [in]; δ – average hard-surface tire deflection [in]; *h* – average tire section height (inflated; unloaded) [in].

Even if the equations (1)–(11) could be simply applied in a classical mathematical software – Python [8] or Matlab [9], here it is written a specific code in VS Command (Fig. 1). This scripting language is used to add extra variables and equations by the well-known vehicle simulation software TruckSim, developed by Mechanical Simulation.

```
Use the field below  for data or commands.
define_output Fz_WC_L1_US=WC_L1_US *cos(ang_slope);
define_output CPF_L1 = 2*Fz_WC_L1_US/(0.5*n_US*d_US*b_US);
define_parameter TEF=(10+b_US)/100;
define_output WLF_L1 = 2*Fz_WC_L1_US /2000;
define_output CF=hc_US/10;
define_parameter GF=1+0.05*CGF;
define_parameter EF=1+0.05*CEF;
define_parameter TF=1+0.05*CTF;
define_parameter CWF1=0.033;
define_parameter CWF2=1.05;
define_output WF_L1 = CWF1*(2*Fz_WC_L1_US/1000)+CWF2;
define_output DCF = (0.15/(defl_US/h_US))^0.25;
define_output MI_L1 = (((CPF_L1*WF_L1)/(TEF*GF))+WLF_L1-CF)*EF*TF;
define_output VCIa_L1=(11.48+0.2*MI_L1-(39.2/(MI_L1+3.74)))*DCF;
define_output VCIb_L1=(4.1*(MI_L1^(0.446)))*DCF;
define_output VCI_WL1= IF_GT_0_then((MI_L1-115), VCIb_L1, VCIa_L1);
```

Figure 1. TruckSim VS Command code for VCI_1 estimation

The procedure is a newest one for this soft that does not have implicit support for terramechanics built-in. It is also part of a bigger project whose objective is to implement the NRMM principles and algorithms for the estimation of the wheeled vehicle mobility performances in a 3D Multi-Body Dynamics software. One step in this direction is to calculate the VCI_1 for each wheel, compared with NRMM that takes into account the average axle loading. Wheel load due to the vehicle position on the slope is also considered. Using TruckSim for this case, the VCI_1 for front axle wheels is estimated to be 26.08 psi, while for rear axle wheels is estimated to be 28.89 psi (Fig. 2).

It can be noticed the difference between the two values which is justified in terms of different wheel loads. However, according to the VCI_1 definition, a single value must be set for the minimum soil strength *RCI* for one pass of the entire vehicle. It is starting from the following principles [3]:

- the soil strength in excess of VCI_1 is known as the excess soil strength and is designated RCI_x;
- the drawbar pull and motion resistance forces are determined using RCI_x;
- the summed of the drawbar pull and motion resistance forces for all powered suspension assembly should be near or 0.

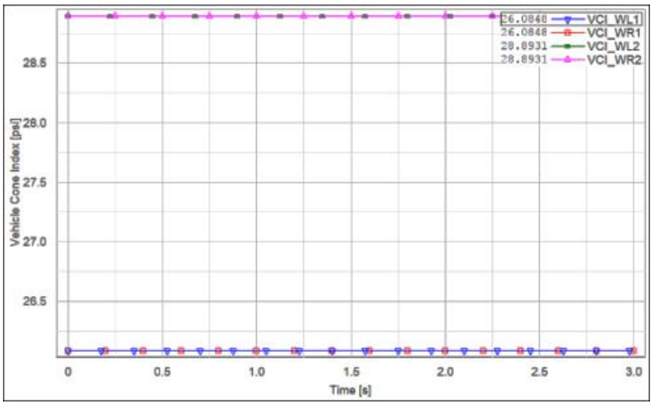

Figure 2. VCI_1 values obtained with TruckSim

In consequence the VCI_1 for the entire vehicle is a value between the two estimated for front and rear wheels. VCI_1 is obtained by varying the *RCI* in the TruckSim model for soft soil, type CH according to Unified Soil Classification System (USCS) [10]. The results – the vehicle speed *V* related to *RCI* are those presented in Table I.

TABLE I. VEHICLE SPEED *V* RELATED TO RCI

No.	*RCI* [psi]	*V* [km/h]
1	29.0	14.04
2	28.5	8.53
3	28.0	7.70
4	27.5	7.60
5	***27.1***	***5.92***
6	27.0	0
7	26.0	0

As a conclusion, the predicted VCI_1 for the entire vehicle is 27.1 psi.

III. VCI_1 TEST IN THE FIELD

TOP 02-2-619A recommend that testing for VCI_1 be done in accordance with ERDC/GSL SR-13-2, a technical report for vehicle acquisition support [11]. The mentioned procedure defines "*site selection criteria, test lane layout, soil data collection procedure, and analysis methodology to determine the* VCI_1". An example of how this procedure was applied on the field, the difficulties encountered as well as the lessons learned are presented below.

A. Site selection

Consistent with ERDC/GSL SR-13-2 naturally occurring off-road lanes must be used for VCI_1 test. Moreover "*test lanes should be a minimum of two vehicle lengths long, relatively straight and level, and of relatively uniform consistency at the point of immobilization*". The *RCI* soil strengths should be near the VCI_1 estimation value. In fact, it is hard to identify such a soil. As example, for this case, the CH fine grained soil *RCI* should be close to 27 psi. On the contrary, on a small area, the *RCI* varies significantly from the minimum of 14 psi to 32 psi. Thus, a lane of vehicle width with uniform characteristics could not be identified.

Also, weather has a great impact on changing the *RCI* within a short time. A small rain made all previous measurements lose their value; like other aspects different from the requirements of TOP 02-2-619A – a slight slope of 2%, local unevenness of the ground with impact on the vehicle ride, and different soil strength critical layer along the path.

B. Equipment used

Cone index *CI* and soil moisture are the soil properties that have been measured during the test.

For the *CI* it was used the manual Eijkelkamp penetrometer, with a measuring range of 0–1000 N. A cone base area of 5 cm^2 was chosen in order to avoid large deviation. Since the *CI* is expressed in N/cm^2, it is necessary to transform the values obtained in *psi* by applying the 1.450377439 multiplying factor.

For volumetric water content it was used the handheld readout device ProCheck by Decagon Devices. The ProCheck interfaces with the soil moisture sensors EC-5 to obtain instantaneous results from 0 to 100%.

Even if the test is a *go* or *no go* type, the vehicle was also instrumented with other equipment:

- Speed measurement was obtained from VBOX 3i 100 Hz GPS Data Logger. From the same supplier – Racelogic, the general-purpose input/output module MIM01 and the 4-channel frequency RLVBFIM03 module were suitable to integrate signals from other sensors (Fig. 3).

Figure 3. VBOX 3i, MIM01 and RLVBFIM03 blue modules

- Engine speed sensor. It consists of the HHT20-ROS Remote Optical Sensor from OMEGA Technologies Company, able to detect a reflected pulse from a target consisting of Reflective Tape at distances of up to 1m from the rotating object and angles up to 45 degrees. A 12 mm square piece of reflective type was applied on the ventilator pulley. The sensor was mounted laterally and optically aligned to illuminate the target once per revolution. The HHT20-ROS works directly with HHT13-KIT Handheld Tachometer (Fig. 4). From HHT13-KIT the signal is acquired by RLVBFIM03 module in order to have a common system for all measured parameters.

Figure 4. HHT13-KIT Handheld Tachometer

- Rear axle transfer case output shaft speed sensor. The Pulsotronic sensor, a polarized retro-reflective laser sensor with 4000 Hz switching frequency together with the reflector were carefully aligned on both sides of the crosshead (Fig. 5). In this way, the light spot, which should be inside the reflector area, is interrupted by the fork arms and gives the signal PNP necessary to measure shaft speed. Using gear ratios, wheel speed is calculated, and implicitly the vehicle theoretical velocity and wheel slip. The Pulsotronic signal is acquired by RLVBFIM03 module in order to have a common system for all measured parameters.

Figure 5. Pulsotronic sensor head, the light spot, and the reflector

- Sensors for real-time measurements of wheel sinkage. These are intelligent laser IL-600 sensors from Keyence with a reference distance of 600 mm and a measurement range of 200 to 1000 mm. Analogue output value is converted to the range from 0 to 5 V and the signal is acquired by MIM01 module in order to have a common system for all measured parameters. Three IL-600 sensors were mounted on the same left size of the vehicle – the first in front part, the second before the rear wheel and the last at the rear extremity of the hull (Fig. 6), all along the front and rear wheel axe.

Figure 6. IL-600 sensor mounted at the rear part

C. Test lane procedure

The military vehicle was prepared in the optimal off-road configuration – all wheels powered, the transmission and transfer case set in the first gear, all differential blocked, and tire deflection adjusted for soft soil.

Vehicle immobilization took place at first pass, any attempt to maneuver the vehicle forward or backward has had no positive effect.

As a consequence, soil properties – *CI* and soil moisture near the point of vehicle immobilization were measured. The sectors with disturbed or influenced soil caused by the wheels were avoided (Fig. 7).

Figure 7. Cone Index and soil moisture measurements

It should be noted that the *RCI* was not physically measured according to the methodology presented in Field Manual (FM) 5-430-00-1 [12]. In the absence of specific equipment such as Hvorslev sampler, drop hammer, remold cylinder and base, specific to the US Army, an estimate of *RCI* was made according to the equations presented in [13]:

$$CI = e^{\left[a - b\cdot\ln\left(m_g\right)\right]} \tag{12}$$

$$RCI = e^{\left[a' - b'\cdot\ln\left(m_g\right)\right]} \tag{13}$$

where:

- m_g is percent moisture content expressed by weight;
- *a, b, a′, b′* are coefficients specified for each USCS type. For CH soil type, in the same order the values are 13.641, 2.417, 13.686, -2.705.

In Fig. 8 is materialized the correlation between the *CI* and the *RCI* based on humidity (12), (13). Also, as an example, the soil moisture and the *CI* values for the left front wheel are displayed on the same picture, confirming the estimation made for *RCI*.

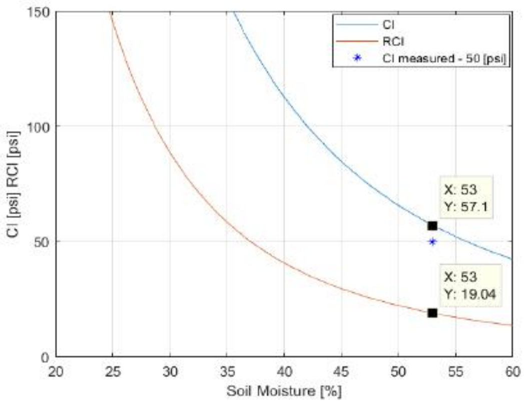

Figure 8. *RCI* estimation for the left front wheel

RCI estimated values based on soil moisture and *CI* measurements at each wheel, using (12) and (13) are presented in Fig. 9.

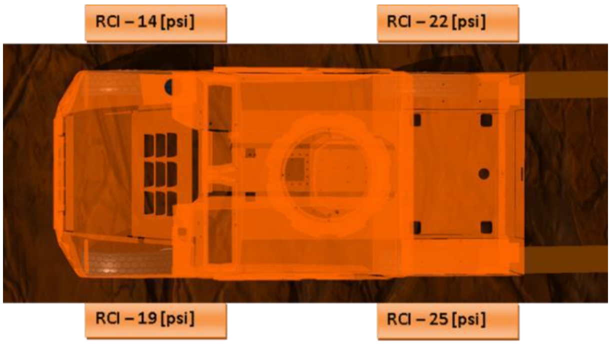

Figure 9. Spatial orientation of soil measurements (plan view)

IV. VCI_1 TEST ANALYSIS

In order to better understand the phenomena that occur when the vehicle reaches the area with the lowest *RCI* soil strength, a simulation of the presented case is done in TruckSim, the results being compared with those from real test.

A. *RCI results*

It is noticed that the *RCI* measured values are well below those predicted for the VCI_1, which leaves no room for interpretation of vehicle immobilization. Furthermore, the difference in strength between the right and left wheel paths is important. This causes the vehicle to sink more on the right side than on the left side, and to lean toward the weaker side (Fig. 10). As a result, there are two drawbacks – the increase of the motion resistance on the right-hand drive and the reduction of the wheel's left adhesion.

Figure 10. Vehicle tilt (spatial view)

Ideally, it would have had *RCI* values of 27-28 psi, uniform along the lanes so that the estimated value for a single pass VCI_1 could be confirmed. This can only be achieved by preparing the soil, which should be accepted in the test standard. This is all the more so since ERDC/GSL SR-13-2 is for an acquisition procedure. The time and spatial variability of *RCI* bring many complications; that is why the testing conditions could be easily contestable. Not to mention a competitive procedure, where vehicles clearly have to go through different lanes, implicitly with differences in texture, structure and organic matter content. As a proposal, for the acquisition procedure or in case of product development, tests should be done in prepared sites. Natural areas for VCI_1 measurements can be recommended in operational testing, when these activities can be associated with training vehicle recovery exercises, more useful for land forces.

B. Wheel sinkage

A careful analysis of what happened in the field shows that the underside part of the vehicle has come into contact with the soil as soon as the *RCI* value decreases from 31.5 psi, the value assigned to the soil before the interested area. An estimate of wheel sinkage as a function of *RCI* is presented in [14], the related relations being as follows:

$$Nc = \frac{RCI \cdot b \cdot d}{W\left(1-\frac{\delta}{n}\right)^{3/2} \cdot \left(1+\frac{b}{d}\right)^{3/4}} \tag{14}$$

$$i_{SP} = \frac{21}{Nc^{5/2}} + 0.005 \tag{15}$$

$$Nc_z = Nc\left(1+\frac{b}{d}\right)^{3/4} \tag{16}$$

$$(z/d)_p = \frac{5}{\left(\frac{Nc_z}{i_{SP}^{1/5}}\right)^{5/3}} \tag{17}$$

$$(z/d)_u = \frac{5}{Nc_z^2} \tag{18}$$

$$(z/d)_n = (z/d) \cdot \sqrt{n} \tag{19}$$

where for (14)-(19): Nc – numeric for a non-steered wheel; W – the tire ground reaction force [lbs.]; i_{SP} – self-propelled wheel slip; $(z/d)_u$ – sinkage coefficient for an unpowered wheel; $(z/d)_p$ – sinkage coefficient for a powered wheel; $(z/d)_n$ – sinkage coefficient for wheel pass n.

For the plot before vehicle immobilization, 0.32 m is the estimation for rear wheel sinkage based on (14), (17), (19). The measured values in the field are in the range 0.25÷0.35 m. In the interested region, the estimation indicates that the sinkage for each wheel should have been the one presented in Table II.

TABLE II. WHEEL SINKAGE ESTIMATION

Estimated wheel sinkage [m]			
Front axle		Rear axle	
Right	Left	Right	Left
1.21	0.56	0.79	0.57

In fact, this level of sinkage cannot be achieved because the belly of the vehicle comes into contact with the ground. Contact forces that appear added to wheel motion resistance forces contribute decisively to the vehicle stopping. One conclusion can be drawn that a bigger ground clearance can help to avoid stumbling when sufficient tractive force exists. The proof that the sinkage could have been higher is in (Fig. 11) where the measured distance by the left front side IL 600 sensor is represented.

The wheel sinkage is more than 150 mm since the vehicle stall, in the context of trying to continue rolling. The wheels totally slip, digging even more into the fine grained soil. This is done consistent with the slip intensity. It can be concluded that in such a situation it is preferable not to try self-evacuation, but to use the winch or to expect a special recovery vehicle.

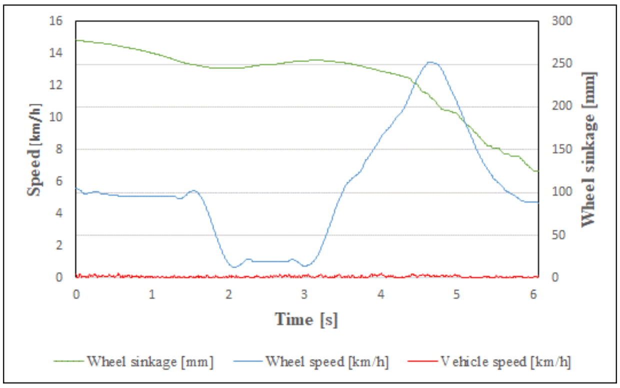

Figure 11. Frontal left wheel sinkage

C. Vehicle pass simulation

The transposition of field test in a virtual medium is done in TruckSim. As inputs are introduced:

- The *RCI* values measured along the lane using the table_define and vs_comand functions;
- 10 km/h speed target before the entry of vehicle in the interested area;
- first gear for gearbox, high gear ratio for transfer case, and all differential blocked.

Also, 4 points were generated near the wheels, on the inner side, at the lowest level of the hull. TruckSim allows the introduction of the 3D vehicle model for animation, but it does not analyze any potential contacts between the underside part and path or other obstacle. This role takes over the 4 points, requiring the condition when one of them comes into contact with the ground to stop the simulation. A comparative illustration of real and simulation results is made for vehicle speed and wheel slip in (Fig. 12). For real-time wheel sinkage, the acquired data was altered by the sprung mass oscillation when passing over bumps. Therefore, a flat land, but also a lower speed would have contributed to better data acquisition.

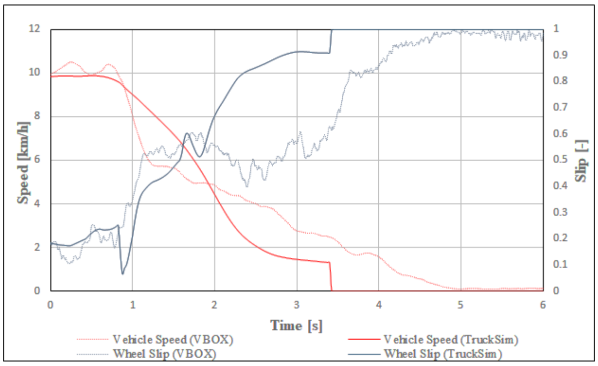

Figure 12. Vehicle speed and wheel slip real test and simulation results

In the simulation, the vehicle stops faster due to the condition required when the underbelly reaches the ground. In reality, for a certain depth firstly, there are phenomena of compaction and detachment, after which a bulldozer effect is created that contributes significantly to stopping the vehicle. For such situations, a solution is to assimilate the UID (Underside Impact Detection) model proposed in [15]. Simulations that reproduce reality with greater fidelity can be obtained with FEM (Finite Element Methods) SPH (Smoothed Particle Hydrodynamics) or DEM (Discrete Element Methods), but to the detriment of the speed of calculation [16].

Another reason why the time and distance to stop is higher is also due to the driver's reaction. From instinct, he released the throttle pedal for almost 0.8 s when the vehicle suddenly began to sink. This phenomenon is deduced from the engine speed variation at that time (Fig. 13).

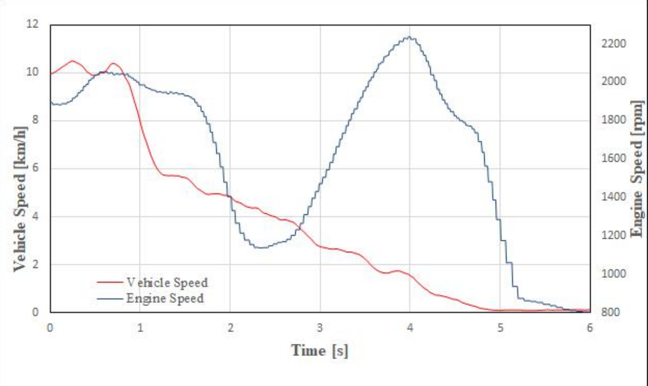

Figure 13. Engine speed

The wheels have gone unpowered, which reduces the level of sinkage. In this way, it turns out that the human factor has an influence in getting better or worse results. Another aspect is given by the number of *RCI* measurements along each side of the test lane. In the simulation, a spline function was used to generate the soil properties based on two values next to the wheels. A 10-point mesh on each side as recommended [11] would lead to a better simulation. Taking into account that for each point are necessary 14 values in the depth it can be concluded that it takes a long time for such action. Instead of a simple penetrometer, ideal for carrying out great numbers of measurements is a penetrologger with internal GPS-system to determine the exact measuring point, with internal ultrasonic sensor to accurately record the depth during insertion of the cone and with soil moisture sensor to register the soil moisture percentage.

V. Conclusion

This article provides both the estimated and measured methodology for VCI_1. In particular, the TOP 02-2-619A and ERDC/GSL SR-13-2 requirements were considered. Aspects from the field testing, also presented in the paper, show how difficult it is to prepare and obtain conclusive data. This is all the more so as the ERDC/GSL SR-13-2 provides that the test be done in natural land even under procurement procedures. Different vehicle characteristics, even from the same range, as well as the human factor, variable weather conditions complicate things a lot. Thus, identifying terrain with strength close to the predicted VCI_1 for each type of vehicle, at close moments is really hard. Rather, the condition for JLTV (Joint Light Tactical Vehicle), which requires a threshold value for *RCI*, is appropriate [17]. This involves only one natural area. Even so, it is more secure to set up a terrain for such a situation, as well as for the development testing of a vehicle. Natural terrain should be used in operational testing when lessons learned earlier would lead to good cooperation between many structures – this would help the combat engineering units in defining the terrain characteristics, the fighter units in establishing the suitable course of action and avoiding the traps that soft soil provides, and, in case of immobilization, it would be the recovery forces to show their abilities and prove the efficiency of the special recovery vehicles.

In the future, the perspective is that these field assessments should be made in advance by simulation, the method presented in this paper fully supporting this concept.

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