# Experimental Modeling of Vehicle Velocity and Applied Load Effect on Tyre Traction in Wet Natural Terrain.

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***Abstract**. This paper presents the results of an investigation into the effect of vehicle velocity and applied load on tyre traction at a given vehicle speed selection in wet clay and sand terrain beds. This experimental investigation was carried out using a highly modified and instrumented wheeled mobility scooter renamed MOBILITY SF-3713. This vehicle was run on hard ground in order to obtain benchmark results. It was then run on sand and clay terrain test beds under controlled laboratory conditions. Results from this experiment indicate that terrain type, applied load, velocity and tyre inflation pressure all have significant effects on net traction output of the vehicle. The results suggest that reliable prediction of this relationship can assist earth moving and deformable haulage road engineers in making economic and operational decisions that affect tractive efficiency of wheeled plant. The results from the experiment were also found to be consistent with the results obtained from the mathematical model developed earlier.*

***Keywords**: Wheel-soil interaction, traction, drawbar-pull, natural terrain*

## Introduction

The performance of a wheeled vehicle traversing in wet and deformable terrain is measured using velocity, wheel rut depths and pulling power measured in form of drawbar-pull, Muleya et al (2014). The effect of wheel rutting on the velocity output has already been addressed in the first part of this research reported in Muleya et al (2014). With full consideration and incorporation of wheel rut depth effect, this paper presents the effect of the generated wheel velocity and the respective applied load on the ultimate performance of the vehicle measured in drawbar-pull. This research was achieved through laboratory experimental modelling with the aim of establishing the most economic factor combinations required to generate maximum and optimum wheel traction for a vehicle traversing in wet natural terrain.

## Background and literature review

Drawbar-pull is considered to be a critical part of off-road vehicle engineering (Wong, 2010). From the Bekker theory, drawbar-pull is defined as the difference between soil thrust and motion resistance and that it defines trafficability, (Muleya, 2014). The net traction force called drawbar-pull is obtained as the difference between the thrust and the resistance force, Ishigami, et al (2011). Saarilahti (2002) defines drawbar-pull, thrust or net pull as the lateral forward force a wheel can develop when moving. It is also defined as the difference between tractive effort and translational resistance (Reid 2000). Grahn 1991, states that the maximum drawbar-pull is the difference between traction force and rolling resistance, Drawbar pull is the force a vehicle can exert on a load in addition to the force required to propel itself, (Parker Hannifin Corporation). This means that if the drawbar-pull value is 0N, the vehicle may propel itself but without power to pull any additional load at the tow bar.

Wheel rutting is also known to significantly affect the pulling power of the vehicle in terms of traction or drawbar-pull, (Muleya, 2014). In planetary exploration, the tractive force produced from the interaction between the wheel and the ground determines the rover's ability to accelerate, climb slopes and cross over obstacles, Favaedi, et al (2011). In an agricultural related study on engine power requirements of movers' in the Malaysian oil planation, Pebrian and Yahya (2010) states that field performance of any off-road vehicle traversing on unprepared terrain depends on the ability of the vehicle to move with the available torques on the drive wheels without constraints under the required drawbar-pull. Drawbar-pull analysis has also been used in military reconnaissance and intelligence in the 'go' or 'no go' movement of military vehicles traversing across deformable terrain. (Madsen et al 2013 and Wong 2010). The forestry industry has also used drawbar-pull analysis in economic management of logging operations. The construction industry is yet to fully utilise this study in the reduction of costs associated with operation of wheeled plant of wet natural terrain. Both wheeled and tracked vehicles have their own merits with respect to their mobility on unprepared terrain. At low speeds tracked vehicles are said to be more superior to wheeled vehicles due to better floatation according to Bygdén and Wästerlund (2007), hence the need to focus on the wheeled vehicles in consideration for optimized traction generation.

### Importance of the study

Positive traction is very essential in vehicle mobility because it defines the economic efficiency of vehicle mobility in a particular terrain. The results from this experiment provide valuable insights on the influence of applied load and vehicle velocity on the generation of maximum traction available measured in form of drawbar-pull. This is particularly important for projects that are time related such as those in the construction industry that deploy medium and heavy duty wheeled earthmoving machinery/plant operating in deformable haulage roads.

## Aim and objectives of the study

The main aim of this study was to model and quantify the combined effect of vehicle velocity and applied load on net tyre traction output on the wheeled vehicles or plant. The study was specific to vehicles operating in wet and deformable terrain using the laboratory experimental approach.

The following were the objectives outlined in order to successfully achieve the main aim stated above:

To model and quantify the tyre net traction based on different tyre inflation pressures, different velocities and five different applied loads on three different terrain beds.

To establish the net traction output on non-deformable pavement as a benchmark or reference point.

To establish the most efficient terrain in terms of net traction generation between wet clay and sand beds.

To establish the most efficient combinations of velocity, tyre/terrain contact area and applied load terrain in terms of net traction generation between pavement, clay and sand beds.

To relate the outcome of the experimental results to off-road operational and contractual related projects.

## Research/Experiment design

The research design was based on quantitative approach in order to obtain values that would be used for comparative and isolated analysis. In order to interpret the results from the clay and sand terrain bed, the special vehicle Mobility SF-3713 reported in (Muleya et al 2014) was run on hard non-deformable terrain in order to establish benchmark or reference results. The decision to adopt laboratory experiments was driven by the existing restrictive health and safety regulations that govern plant manufacturers testing sites and earth moving contractors. Velocity, applied load and drawbar-pull values were obtained by means of instrumentation and recording of physical measurements as described in section 6 below. Scaling and correction factors must apply to the simulated results for full scale running of wheeled plant. In addition, laboratory experiments have the advantage of controlling the consistency of the multiple runs that have to be done by changing the measurable values of the research outputs. The laboratory conditions provide more control of the experimental procedures such as protection from external factors which include weather, temperature and soil test bed re-building (Muleya et al 2014). Sand and clay terrains were selected for this experiment because they constitute the most common soil profiles. In addition these two types of soil have engineering properties that can be easily defined and measured.

Figure 1: Modified and instrumented Mobility SF-3713

## Drawbar-pull laboratory experiments based on MOBILITY SF-3713

The new sovereign mobility scooter shown in figure 1 was disassembled, redesigned and rebuilt to meet the objectives of the study. A specially designed frame and platform was mounted to carry the varied weights of 20kg for each unit weight that represented the applied loads of up to 80kg which were critical during the isolated analysis procedures.

The special vehicle was run on inflatable pneumatic tyres of size 260 x 85mm to enable the change of tyre inflation pressure with the purpose of adjusting the tyre/terrain contact area. The tyre pressure was measured with a special instrument called PCL tyre gauge as shown in figures 2 and 3. The two tyre inflation pressures selected were 10PSI and 45PSI. The two tyre inflation pressures were used on the three terrains, various applied loads and various velocities.

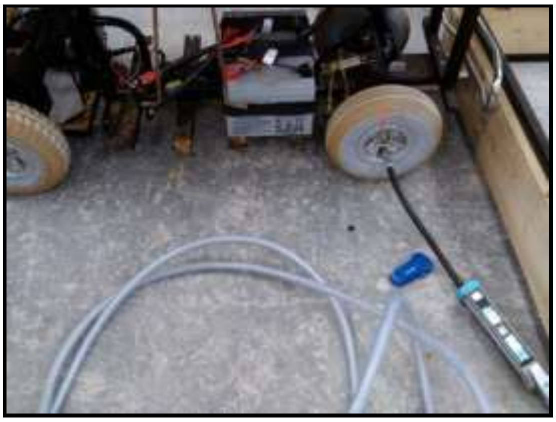

Figure 2: Tyre inflation in progress using compressed air

Figure 3: Digital tyre pressure gauge/reader

The velocity was calculated by dividing the distance travelled in metres by the time taken in seconds. The time was recorded by an operator timer and the camcorder timer with the final value being the average of the two. This procedure was used for all the three terrains beds under investigation. The advantage with this special vehicle is that it moved freely without guided rails in contrast with what has been presented in many other studies as seen in lagnemma et al (2004) and Ding et al 2010). This gave more credible results in terms of attaining practical patterns of running the experiments as they would be during the live onsite experiments. This was very critical in the establishment of drawbar-pull values from the unrestricted movement of the vehicle which simulated the live running of a wheeled vehicle.

Finally, the net traction values were measured in terms of drawbar-pull with Newtons as units on all experiments encompassing different tyre pressures, weights and velocities. A slack-less chain was securely attached to the machine in order to obtain the maximum and accurate drawbar-pull values available with the given conditions. The drawbar-pull values were obtained and recorded using a special load cell dynamometer and the PCE-1000 force gauge shown in figures 4, 5 and 6. The load cell had a maximum capacity of 100Kg or 1000N. The load cell was connected to a digital gauge/reader via a cable

Figure 4: Dynamometer load cell and PCE-1000 force gauge

Figure 5: Dynamometer load cell in use


Figure 6: Mobility SF-3713 pulling its own weight to measure maximum force available using the dynamometer load cell and PCE-1000 force gauge

**Determining the actual velocity for each speed selection**

Figure 7 shows the sand bed with the acceleration allowance length while figure 8 shows the clay bed. Both materials were compacted just enough to support the special vehicle and to simulate terrain in its natural state.

## 7.0. Soil bed parameters

The timber and steel formwork used for the sandy and terrain beds was 3 metres long, 1 metre wide and 0.20metres high. The sand ordered had moisture content of 6.3% in order to obtain the credible results that would be consistent with the outlined objectives. The sand bed mould was filled with sand in layers of 50mm which was gently compacted just enough to simulate a realistic natural terrain that would be representative of the moist dense sandy terrain. The sand and clay terrain beds were prepared every time after running the experiment in order to create a bed of undisturbed terrain. Sand was much easier to manage in preparation, handling and disposal due to the less-cohesive nature of the sand.

The internal friction angle of sand was found to be 31$^{o}$ which is consistent with average for the soil of this nature. The clay material used was equally compacted enough to represent natural terrain. It had moisture content of 31% and a bulk density of 1.98Mg/m$^3$. The soil cohesion established through tri-axial machine was 74KN/m$^2$.

Figure 7: Laboratory experiment sand bed showing acceleration allowance distance (Muleya et al, 2014)

Figure 8: Laboratory experiment clay bed compacted just enough to support the special vehicle and simulate terrain in its natural state, (Muleya et al, 2014)

## 8.0. Results and discussion from the experiments

The section below presents the experiment results demonstrating the relationship between vehicle velocity/applied load and vehicle tyre net traction measured in form of drawbar-pull through experimental modelling. The experimental runs were characterised by five different applied loads, two tyre inflation pressure values (low and high) and three types of terrain as stated in section 6 of this paper.

### 8.1. Effect of vehicle velocity and applied load on drawbar-pull on the hard ground

The increase of speed selection values was proportional to the velocity generated as seen in figure 12 however the drawbar-pull generated was not proportional as seen in figure 13. All velocities including the maximum (1.53m/s), produced the highest drawbar-pull values on the hard ground (630N to 670N) from the all combinations of tyre pressure/applied load except for the 3PSI/0N and 45PSI/0N which produced lower drawbar-pull of 330N and 410N respectively. This can be seen in figures 12 and 13. The results demonstrate that introduction of applied load is very critical in the generation of drawbar-pull and the much needed net traction for the tyre and vehicle stability regardless of velocity level. The increase in the tyre contact area increases the generated drawbar-pull as demonstrated in figure 9. As seen from the results tyre traction is not only essential in off-road conditions but on pavement roads as well. The primary influence of rut depth on the velocity produced was discussed in (Muleya et al, 2014).

### 8.2. Effect of vehicle velocity and applied load on drawbar-pull on the sandy terrain bed

In the sandy terrain bed, the increase of speed selection values is proportional to the velocity generated as seen in figure 14. The 3PSI lower tyre pressure however produced the higher velocity than the 45PSI tyre pressure. In this experiment the 3PSI/800N produces the maximum drawbar-pull of 330N from the lowest and highest velocities, 0.52m/s and 1.71m/s respectively as shown in figures 14 and 15. The overall drawbar-pull values are far much lower compared to the output from that hard ground experiments as seen in figures 13 and 15. The results suggest that increase in velocity does not necessarily improve the drawbar-pull output in wet sandy terrain. All other drawbar-pull outputs from the tyre pressure/applied load combinations other than the 3PSI/800N diminish with increase in velocity. The least drawbar-pull was produced from the lowest lower tyre/terrain contact area experiment from the 45PSI tyre inflation pressure as shown in figures 10 and 15.

Lower tyre inflation pressure and wider tyre/terrain contact area provided better performance through reduced rutting. Additional load in this combination provided more traction and stability resulting in the engine energy turning the wheels rather than digging in the ground. This result suggests that wheeled and loaded vehicles generate lower power output/efficiency in the sandy soil bed particularly if the tyres are fully inflated with small tyre/terrain contact area. This also implies that a wheeled vehicle with 0N drawbar-pull may only propel itself but unable to pull or carry any additional load.

### 8.3. Effect of vehicle velocity and applied load on drawbar-pull on the clay terrain bed

The rate of increase of speed selection was proportional to the velocity generated as seen in figure 16. The pattern was also similar to that from the hard ground in figure 12 signifying the stable nature of clay terrain to adequately support the wheeled loaded vehicle. Despite this consistency in the velocity pattern, the velocity outputs are not proportional to the drawbar-pull outputs as seen in figure 17. In this experiment all applied load/tyre pressure combinations produced significant and high drawbar-pull up to speed selection 3 as shown in figure 17. These include the ones with lower tyre/terrain contact area as 400N/45PSI, 0N/45PSI and 800N/45PSI. These combinations however produced diminishing drawbar-pull with every increase in velocity with the 0N/45PSI combination producing the least drawbar-pull because of the lowest contact area and 0N applied load.

On the other hand the larger tyre/terrain contact area combination continued to produce significant positive drawbar-pull despite have diminished increase. The combinations with more efficient drawbar-pull included 0N/3PS1, 400N/3PSI and 800N/3PSI. These results clearly demonstrate that the lower tyre/terrain contact area created by the high inflation tyre pressure produced maximum drawbar-pull at lower velocities as seen in figure 17. On the other hand larger tyre/terrain contact area created by the 3PSI tyre inflation pressure produces maximum drawbar-pull between speed selections 5 and 7 at minimum velocity of average 1m/s for the top velocity value. The results present another strong indication that larger contact area and applied load is required to generate positive drawbar-pull for net tyre traction even in clay terrain bed. The generation of drawbar-pull is much similar to the runs on the hard ground. The results suggest that even in clay soil the larger contact area is still essential in the generation of drawbar-pull. Drawbar-pull results in the clay terrain bed are closer to that of the hard ground as seen from the experiment results.

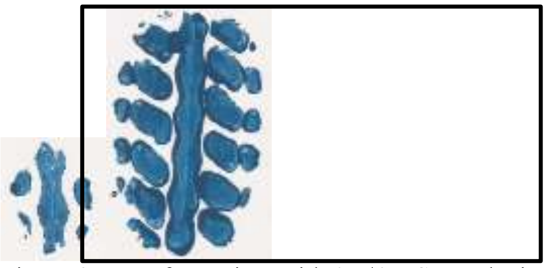

Figure 9: Tyre foot prints with 0N/45PSI producing lower drawbar-pull on the left pane and 800N/3PSI producing the highest drawbar-pull on the right pane on pavement terrain.

Figure 10: Minimum drawbar-pull generation from the vehicle running on the sand bed terrain at maximum speed with 800N/45PSI.

Figure 11: Maximum drawbar-pull generation from the vehicle running on the sand bed terrain at maximum speed with 800N/3PSI.

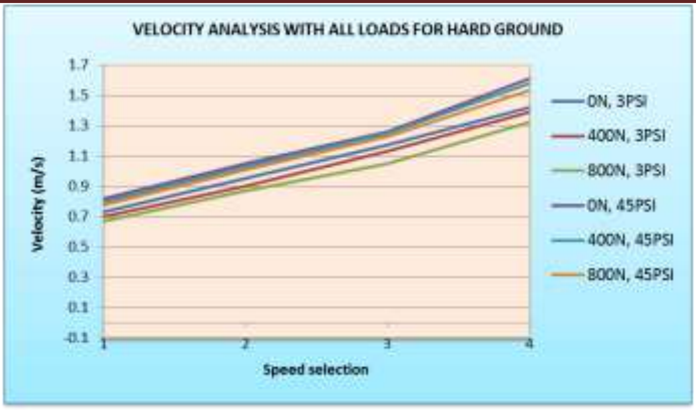


Figure 12: Velocity rut depth analysis on hard ground

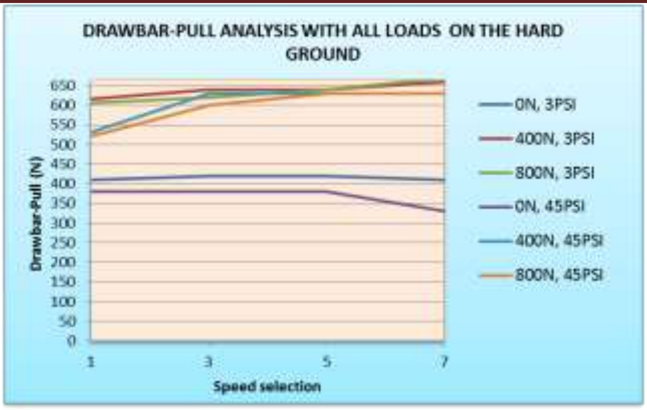


Figure 13: Corresponding drawbar-pull analysis on hard ground

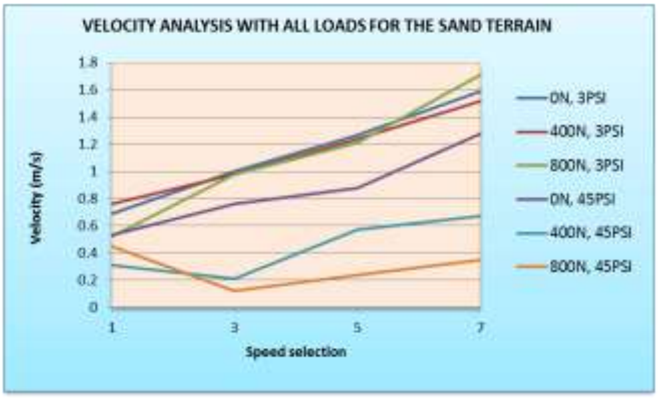


Figure 14: Velocity rut depth analysis on sandy terrain bed

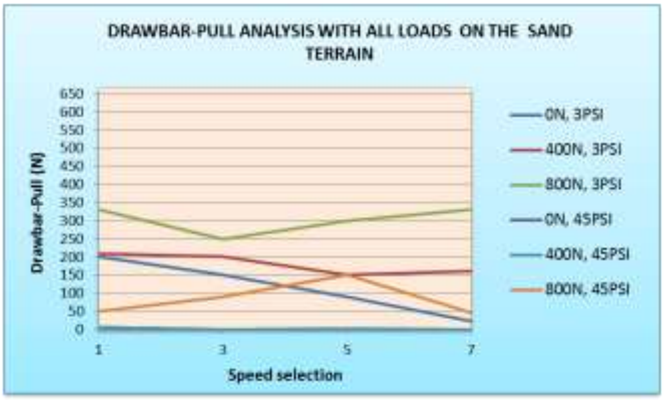


Figure 15: Corresponding drawbar-pull analysis on the sandy terrain bed

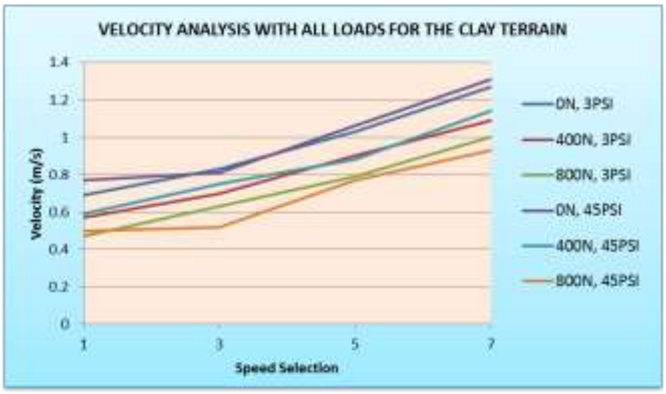


Figure 16: Velocity rut depth analysis on clay terrain bed

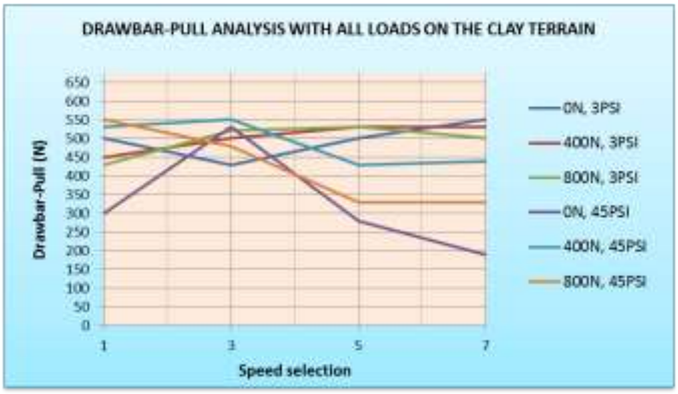


Figure 17: Corresponding drawbar-pull analysis on the clay terrain bed

## Conclusions and recommendations

From the experiment results presented in this study, the following conclusions and recommendations have been drawn:

The contact area between the tyres and the terrain has significant influence in the generation of net tyre traction despite not experiencing any tyre sinkage on the non-deformable pavement. Larger tyre/terrain contact area provides more drawbar-pull available at the tyres than smaller contact area. This can be achieved by using wider tyres and/or reduced tyre pressure to safe specifications. The increase in velocity does not necessarily translate into corresponding increased drawbar-pull. This is a very important outcome for the economic management of wheeled vehicles traversing even on non-deformable terrain such as pavement roads.

The drawbar-pull generated between the tyres and terrain in wet dense sand was much lower than the one generated from the hard ground. The study also concludes from the experiment that the same values of drawbar-pull are generated from the minimum and maximum velocities. Increasing velocities and applied load resulted into diminished traction values. This means that all the increase in energy to the tyres is wasted because it does not improve any traction. Sand must be saturated with moisture and dense enough to support loaded vehicle in order to generate some drawbar-pull. Wider tyres are equally essential in wet dense sand. The results provide important information for planning engineers and managers in the management of wheeled plant operating in sand dominated terrain.

The drawbar-pull values generated in the wet clay bed were similar to the one generated on the hard ground. Both low and high tyre pressure/applied loads were efficient for the first two speed selections, however only larger tyre/terrain contact area runs produced constant drawbar-pull. Highly inflated tyres with smaller tyre/terrain contact area produced rapidly diminishing net traction values regardless of the loads applied. The contact area still played a very significant role in the generation of drawbar-pull in the wet clay terrain bed.

The conclusion can be drawn that the drawbar-pull output in wet clay terrain is better than in the wet sand terrain. The conclusion can now be used in the determination of wheeled plant management when operating in wet and deformable natural terrain.

The experiment however did not consider the effect of various moisture contents, effects of various tyre sizes and combination of sand and clay terrain beds. Despite these limitations the original objectives of the study were successfully achieved.

As mentioned in Muleya, et al 2014, scaling and correction factors are required when the models are applied to full scale analysis. Selected field tests on the other hand may be required to provide provided realistic, practical data in order to validate some sections of the mathematical, simulation and laboratory based models.

The paper is recommending consideration of introduction of tyre pressure control system to commercial vehicles operating in wet off-raod conditions. This can also lead to further development of algorithms that can be incorporated in the outcome of this study to automatically adjust tyre pressure based on real time terrain properties. This requires the collection of data from wheeled plant using the current specifications. Such a tool in the vehicle would be reliable enough to automatically regulate the tyre pressure in order to attain the desired drawbar-pull parameters. This research will need a significant input from the automotive design and manufacture industry that will be required to design and build sensors that would meet the laid down objectives. Such technology already exists in the American Defence Department according to the Clemson University vehicular electronics laboratory in South Carolina.

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Franco Muleya graduated from the Copperbelt University in Zambia in 2001 with BSc Building Science. He later graduated from the University of Manchester in 2006 in MSc Management of Projects. He is currently completing his PhD at Anglia Ruskin University in England where his research is based on modelling wheeled construction plant performance in natural terrain, a section of off-road vehicle engineering governed by terramechanics. He is currently tutoring civil engineering concrete technology laboratories and introduction to design and technology at Anglia Ruskin University. He is also a lecturer on study leave at the Copperbelt University in the department of quantity surveying and construction management. Mr. Muleya has also served in various portfolios in the practicing industry as a construction site engineer, senior quantity surveyor/estimator and quality assurance/control engineer for building, civil and mechanical engineering works. He is a registered quantity surveyor and an incorporate member of the Chartered Institute Of Building.

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### Dr. David Reid.

Dr David Reid is a retired senior lecturer and deputy dean in the science and technology faculty of Anglia Ruskin University in England. He holds a BSc, MSc. He has a PhD in mathematical modelling of wheel rutting in deformable wet terrain from Nappier University in Scotland. He is a chartered engineer and chartered mathematician. His research areas include Dynamic loading of structures, Vibration analysis of bridge decks, Vibration analysis of timber flooring systems, mathematical modelling applied to terramechanics, mathematical modelling of plastic pipe trench reinstatements, Non-destructive testing of highway structures. He also served as a member of Joint Board of Moderators for the Institution of Civil Engineers, member of Council for the Institute of Mathematics and its Applications. He has also been a visiting Professor to Liaoning University, Jinzhou, China.