

Wheel Force Transducer Research and Development

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W911NF-10-1-0463

Final Report.

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14. ABSTRACT This document forms the final report on the development of a concept wheel force transducer that can measure the forces and moments between a tire and a road on a HMMWV driven under off-road conditions. This concept development is part of a project that endeavors to develop, validate and calibrate cost effective field test equipment for measuring tire characteristics on vehicles whilst driving off-road. The proposed wheel force transducer is an important step in a renewed research effort that aims to correct the gap in current tire testing and modeling knowledge to ensure that future off-road vehicle models and simulation efforts are conducted with confidence. The report briefly describes the manufacturing, assembly and calibration of 4 wheel force transducers for use on the HMMWV. An interface drawing, for fitment of the wheel force transducer to other vehicles, is also supplied.					
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Abstract

This document forms the final report on the development of a concept wheel force transducer that can measure the forces and moments between a tire and a road on a HMMWV driven under off-road conditions. This concept development is part of a project that endeavors to develop, validate and calibrate cost effective field test equipment for measuring tire characteristics on vehicles whilst driving off-road. The proposed wheel force transducer is an important step in a renewed research effort that aims to correct the gap in current tire testing and modeling knowledge to ensure that future off-road vehicle models and simulation efforts are conducted with confidence.

The report briefly describes the design, manufacturing, assembly and calibration of four wheel force transducers for use on the HMMWV. Interface drawings, for fitment of the wheel force transducer to other vehicles, is also supplied.

1. Problem statement

Obtaining tire characteristics on off-road terrain for use in tire models, as well as suitable tire models represent a significant research challenge. A first, but extremely important step in this research is to develop suitable tire test equipment. Due to the difficulty of simulating off-road terrain under laboratory conditions, field test equipment, that can determine tire characteristics on vehicles whilst driving over these terrains, is required.

2. Objectives

In order to obtain tire characteristics over off-road terrain, cost-effective field test equipment is required. The proposal therefore has four main objectives^[1,2]:

- a) Develop a prototype 6-component wheel force transducer to measure tire forces and moments on a vehicle whilst driving
- b) Develop mathematical models of the wheel force transducer
- c) Validate and calibrate the wheel force transducer
- d) Manufacture a set of four wheel load cells for fitment to a vehicle.

This report describes the design, development and manufacturing of four wheel force transducers for fitment to a HMMWV.

3. Client requirements

The client requires that the forces and moments between the tire and the road must be measured on a HMMWV vehicle. There are many derivatives of the HMMWV with large differences in mass. As reference, the M1165A1 w/B3 version is used^[3]. The gross weight of this vehicle is 5479 kg (12100 lbs.) with 2404 kg on the front axle and 3175 kg on the rear axle. The static vertical load on a rear wheel is therefore taken as 1600 kg and the wheel load cell is designed for a maximum vertical load of 3 times the static load or 4800 kg. The main design requirements for the wheel force transducer are summarized in Table 1.

Table 1: Design requirements

Item	Parameter	Value
1	Static vertical wheel load	1600 kg (rear wheels)
2	Maximum vertical wheel load	4800 kg (extreme case)
3	Rim size	16.5" diameter 8.25" wide
4	Flange dimensions	8 studs on 6.5" PCD
5	Unsprung mass	Not specified, but needs to be kept as low as possible

4. Concept design

The concept design of the wheel force transducer, where the space envelope, layout, basic dimensions and expected load was determined, was discussed in the first interim report^[4].

The space envelope and therefore basic dimensions available to fit the transducer, is dictated by the rim. Figure 1 indicates the basic dimensions of the standard military HMMWV split rim. Due to the suspension

components on the inside of the wheel, the transducer must be mounted to the outside of the standard rim.

The wheel force transducer replaces part of the rim so that the rim is connected to the hub via the force transducer. To achieve this, the standard rim is modified. Figure 2 shows the standard rim on the left and the modified rim on the right. Modification is simple and involves cutting out the center portion of the outer part of the original rim to the same diameter as the unmodified inner rim.

The possibility exists to mount the wheel force transducer to other rim sizes and designs. The exact possibilities depend on the geometry of the different rims but basically entail designing and manufacturing adapters to connect the load cell inner ring to the rim and the load cell outer ring to the hub. This can also be turned around so that the load cell inner ring is mounted to the hub and the load cell outer ring is mounted to the rim.

The force transducer is however currently designed for a static load of 1600 kg (maximum load of 4800 kg). This has two implications when using this transducer in different applications namely:

- a) If the static and dynamic loads are significantly lower, then the load cell sensitivity will be reduced
- b) The strength required from the load cell influences the mass. If the load cell is used on a smaller vehicle, the increase in unsprung mass might become a problem.

Better sensitivity can be achieved fairly easily and cost-effectively by replacing the 6 individual load cells per wheel force transducer with suitably scaled versions, but the unsprung mass increase may still be a problem.

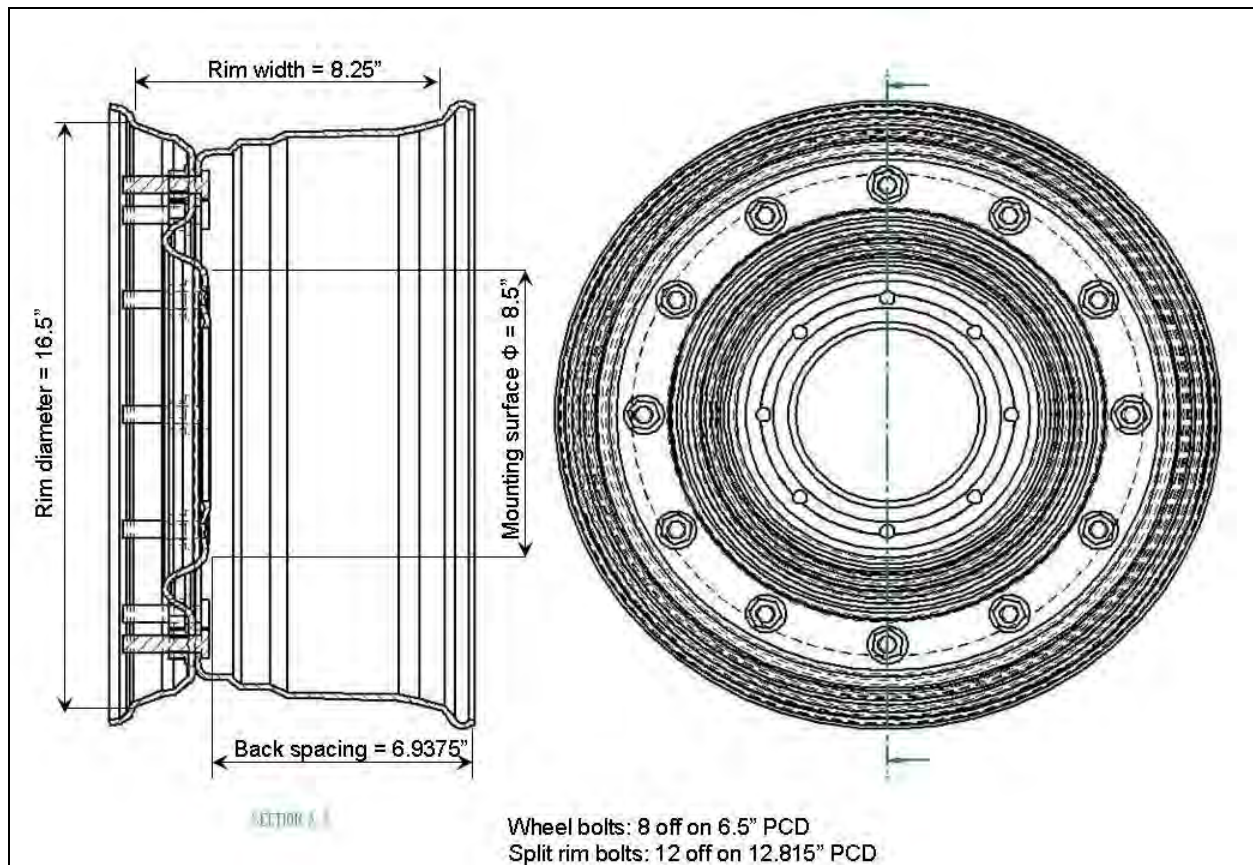


Figure 1 – Standard HMMWV rim dimensions

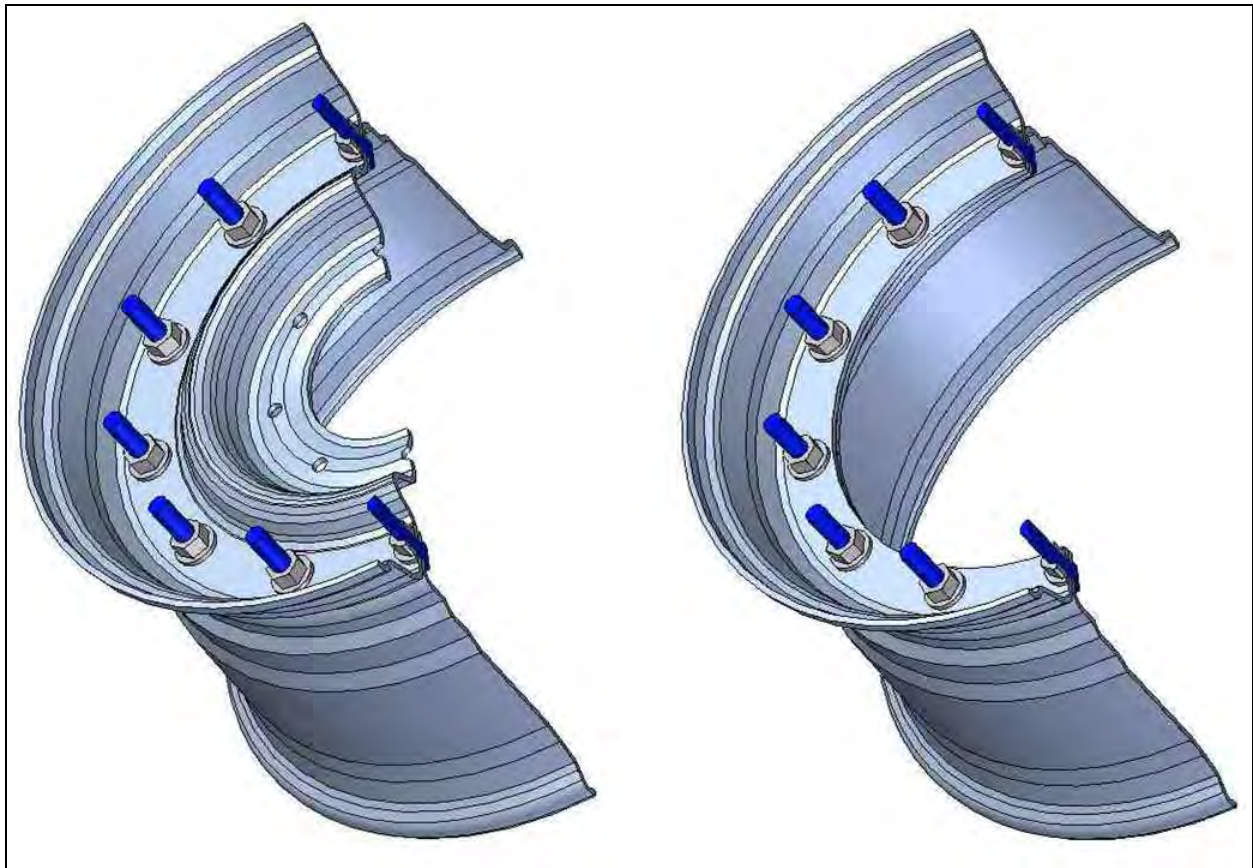


Figure 2 – Standard and modified rim

5. Detail design

The detail design of the wheel force transducer was described in the 2nd Interim Report^[5]. Apart from finalizing the dimensions and layout, the detail design addressed two aspects namely sealing and strength.

V-ring seals are used to seal the spaces between the different parts of the wheel force transducer to prevent foreign objects from entering the transducer. These seals make the transducer splash proof and seal against dust, sand, mud etc. It will however not be water proof when submersed.

Strength was analyzed by performing a Finite Element Analysis (FEM) on two load cases that are considered to be worst case. The applied load in each case is 50 kN (or 5 000 kg). This means that the vehicle can land with the full vehicle weight on one wheel and that only one of the six load cells in the wheel force transducer can carry the entire load. This resembles an extreme load case.

Finite element analysis results indicated that the load cell flanges can be manufactured from Aluminium 7075 alloy in the T6 heat treatment condition. The use of aluminium also has a large advantages in terms of weight as well as corrosion.

The mass of the wheel transducer is 21 kg and the HMMWV hub adapter is 8 kg giving at total mass of 29 kg in the HMMWV application. The existing HMMWV tire and rim weighs around 70 kg. The change in unsprung mass caused by the wheel force transducer is therefore deemed acceptable.

6. Design validation testing

Testing performed to validate the design was described in the 3rd Interim Report^[6].

Material test specimens were tested at different fully-reversed tension-compression force values and the number of cycles until failure were counted. The initial fatigue life of the specimens were not satisfactory but it was found that increasing the radius and polishing significantly increases the fatigue life. The original flange design was subsequently modified to reduce the stress concentration at the critical point by increasing the radius and adding more material. The results were again verified with Finite Element

Analysis. The flanges are now expected to have a life in excess of 1 million cycles at the extreme load case. Given the HMMWV wheel diameter of 0.9 m, this represents a circumference of 2.8 m and a distance of around 2800 km at this extreme loading case.

A test flange was manufactured and fatigue tested. Initial fatigue testing indicated that the load cells and load cell pins are not strong enough. The load cell pin diameter was subsequently increased from 12 mm to 17 mm and the shoulder in the initial pin design was removed to eliminate the stress concentration. The 12 mm diameter spherical bearings were replaced with 17 mm bearings. The load cell design was changed to reduce stress concentrations and the load bearing area was increased.

Fatigue testing on the test rig, as indicated in Figure 4 (performed at a load of 30 kN) was stopped when the top aluminium test piece completed 1.1 million cycles and the bottom piece 1.3 million cycles without any visible cracks. This life is considered more than adequate as this means that the vehicle can drive, with the full vehicle load on a single wheel, for more than 3 600 km. As the wheel force transducer is a piece of test equipment, that will only be used under controlled conditions for dedicated tests, this life is more than acceptable. The load cell pin is the weak point currently. This is good as this is the least expensive part in the load cell and can therefore be checked and replaced each time the load cells are removed for calibration.



Figure 3 – Fatigue testing

7. Validate and calibrate the wheel force transducer

The individual load cells used in the wheel force transducer are indicated in Figure 4. These load cells were calibrated using Schenck Hydropuls test equipment as indicated in Figure 5. Calibration values for each individual load cell are given in Table 2. Table 2 also indicates the specific wheel force transducer and the position in which each load cell was assembled.

Figures 6 to 8 indicate one of the prototype wheel force transducers during assembly.

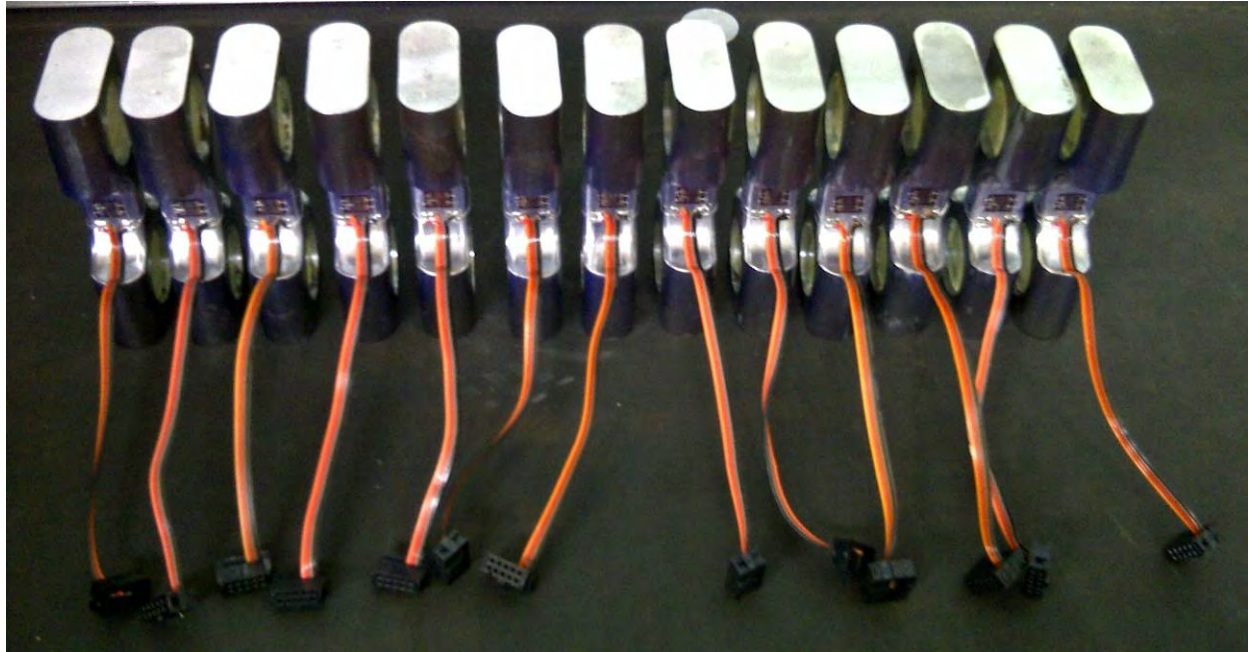


Figure 4 - Individual load cells ready for calibration

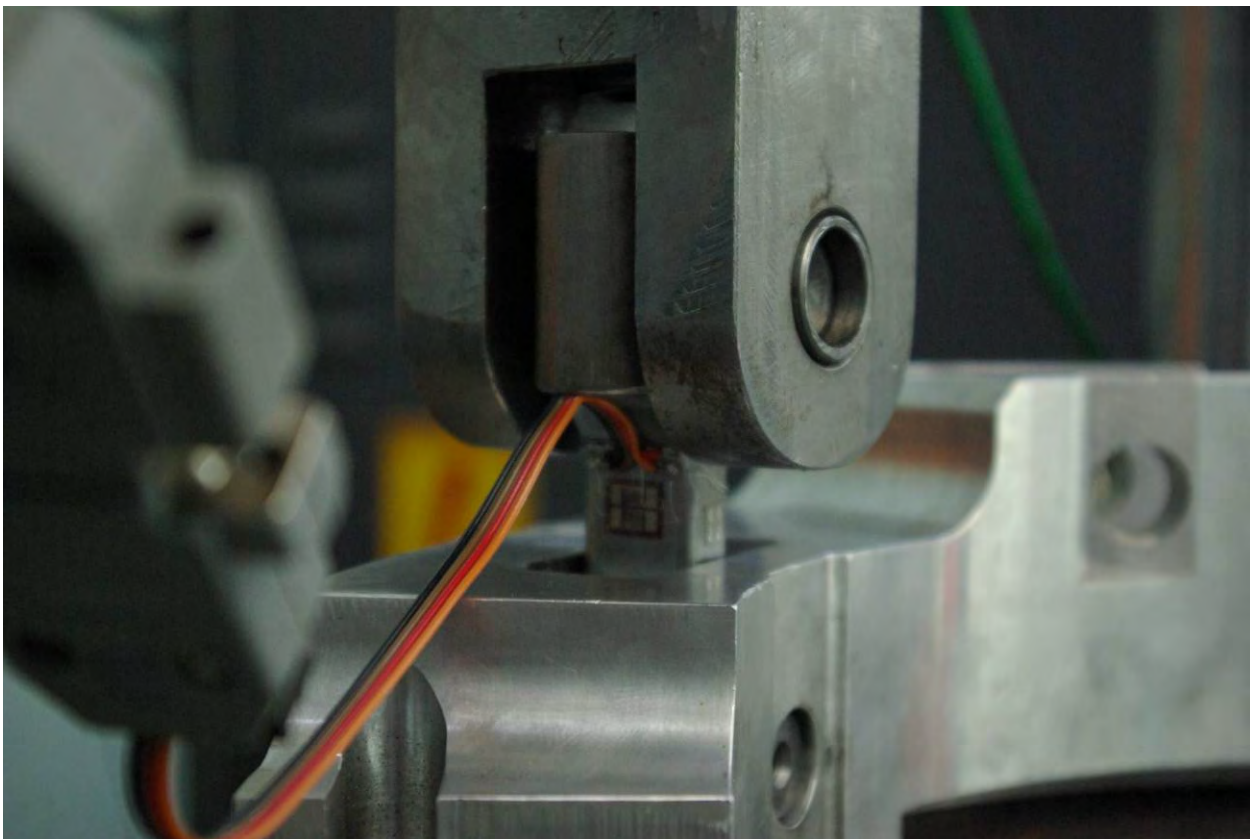


Figure 5 - Load cell under calibration



Figure 6 - Components of a wheel force transducer

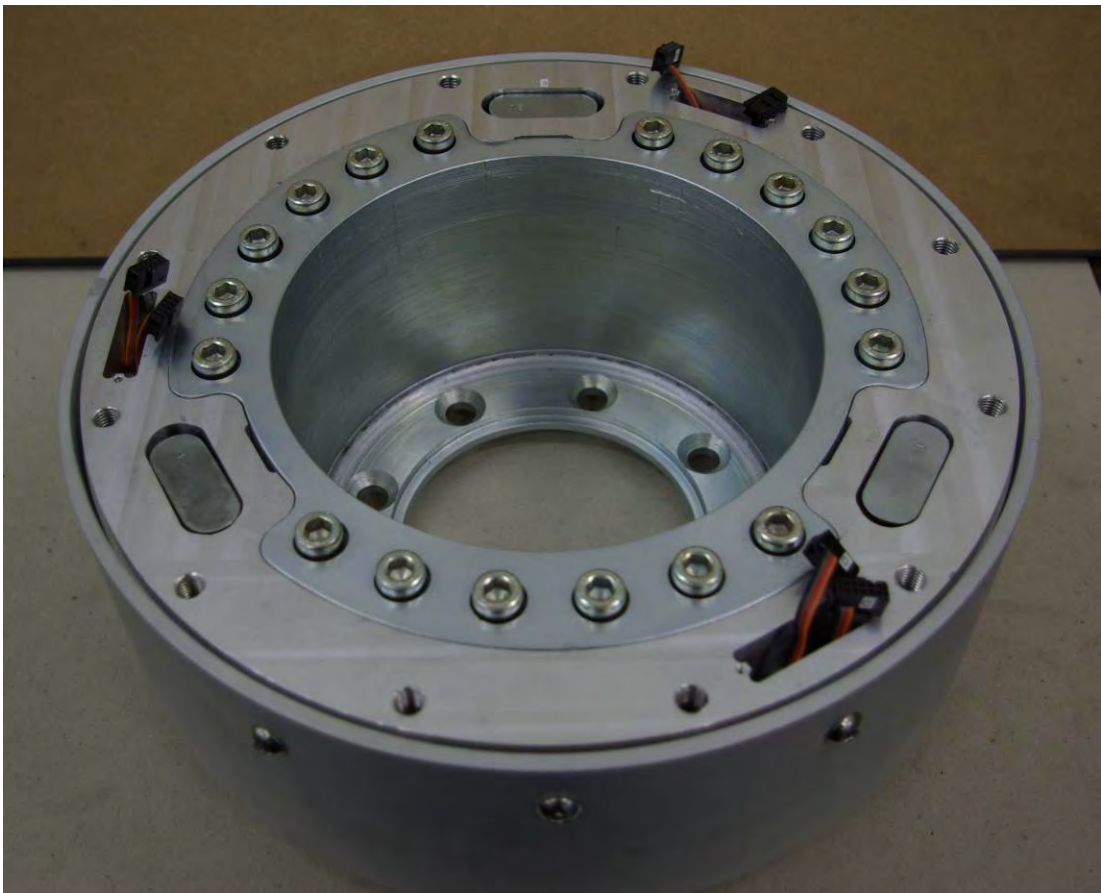


Figure 7 - Assembled wheel force transducer, outside view (without cover)



Figure 8 - Assembled wheel force transducer inside view (vehicle side)

8. Manufacture a set of four wheel force transducers for fitment to a vehicle.

The set of four wheel force transducers were manufactured, assembled, calibrated and shipped. Figure 9 indicates the four transducers packed in the crate, ready for shipping.

9. Telemetry requirements and options for use with the wheel force transducer:

The telemetry was not included in this study and has to be procured separately. Recommendations in this regard are now made.

The following requirements are set out for each of the four wheel force transducers:

- 6 off: 350 Ω full bridge strain gage inputs (around 1.6 mV/V sensitivity)
- 2 off: Analog inputs for wheel rotation angle measurement (must supply excitation voltage of around 3 to 10 Volts to sensor and read back a full scale value equal to the sensor supply voltage)
- 1 off: Input for “synchronization trigger”. This can be an analog or digital input to measure trigger pulses from a sensor triggered by a fixed point on the vehicle. This must be recorded simultaneously on the data recording system on the vehicle to enable the data to be time-synchronized during post-processing.
- Extra inputs may be required for measuring tyre temperature, tyre pressure etc. For each wheel, if required.

Table 2 – Individual load cell calibration and assembly configuration

Load Cell Serial Number	Calibration value [N/V] Amplifier Gain = 500	Sensitivity [mV/V]	Wheel assembly	Position In wheel assembly
1	6275.5	1.591	1	A
2	-6276.1	1.715	1	B
3	-6368.6	1.624	1	C
4	6276.5	1.581	1	D
5	-6580.2	1.577	1	E
6	6359.8	1.577	1	F
7	-6482.7	1.598	2	A
8	-6035.6	1.684	2	B
9	-6159.2	1.678	2	C
10	-6404	1.631	2	D
11	-6063.1	1.695	2	E
12	6172	1.615	2	F
13	6349.8	1.572	3	A
14	6251.1	1.590	3	B
15	-6299	1.635	3	C
16	6282.1	1.566	3	D
17	6368.5	1.574	3	E
18	-6190	1.636	3	F
19	6118	1.627	4	A
20	-6101.9	1.700	4	B
21	6389.8	1.569	4	C
22	6349.2	1.568	4	E
23	-6412.6	1.608	4	D
24	6352.2	1.570	4	F

Telemetry options:**Option 1:** V-link (Microstrain)

<http://www.microstrain.com/v-link.aspx>

Each V-link contains:

- 4 off full bridge inputs with 3 V excitation
- 3 off analog inputs with 0-3 V range
- 3 V excitation for additional sensors
- 1 off temperature input

Advantages:

- Need only 2 V-link units per wheel + 1 “dummy” for balancing.
- Costs around US\$ 1000 each or US\$ 2000 per wheel
- Simultaneous triggering for all nodes
- 2 extra bridge inputs and 3 extra analog inputs available per wheel for additional sensors
- Data is downloaded directly to a PC or laptop via an antenna connected to the USB port, i.e. no additional analog data channels required.
- 2048 Hz max sampling frequency

Drawbacks:

- Data needs to be downloaded individually per node – time consuming operation (Might be solvable using custom software)
- Files need to be copied, renamed etc. (Might be solvable using custom software)

- Sampling time is fixed and has to finish before downloading can commence (Might be solvable using custom software)
- 1 000 000 samples can be stored, i.e. 61 seconds for 7 channels sampled at 2048 Hz (or 10 minutes at 204 Hz which is more than high enough for vehicle dynamics measurements)
- 8 minutes to download full memory per V-link

Potential issues:

- Battery life (6h when logging)



Figure 9 - Four wheel force transducers in crate

Option 2: KMT telemetry

- 8 Channel version see: <http://www.kmt-gmbh.com/neu/ct48wheel-telemetry-p-43.html>
- 16 Channel version see: <http://www.kmt-gmbh.com/neu/ct16-rotate-telemetry-p-55.html>

Advantages:

- 8 (or 16) Channels can be individually configured (e.g. 6 off strain gage bridge and 2 off analog inputs)
- Output is analog, so no synchronization problems

Drawbacks:

- High cost, about US\$ 27k per wheel for 8 channel version
- Only 8 channels on the “cheaper” version available
- Need 32 additional channels on normal data acquisition system thus you will require 32 additional channels to be measured on the vehicle.

Potential issues:

- Battery life (6-12h according to spec)

Other options (not investigated in detail):

- System developed by Prof Massimiliano Gobbi from Polytechnic di Milano, Italy
- Our own development is in process
- Other commercial options:
 - i) <http://www.atcom.fr/fr/telemetrie/wheel-telemetry.pdf>
 - ii) <http://www.atitelemetry.com/viewproduct-6108.htm>
 - iii) http://mon.email.free.fr/FTP/Docs/Caemax/R2_DE.pdf
 - iv) http://www.michsci.com/Products/telemetry/pdf/Torque_Wheel_Telemetry_Flyer_a.pdf

10. Interface between wheel force transducer, rim and hub

To use the wheel force transducers on rims other than that of the HMMWV, adapters must be made. One flange of the wheel force transducer must be connected to the hub and the other flange to the rim. The wheel force transducer is symmetrical, so it doesn't matter which of the two flanges are connected to the rim or hub. There are three sets of holes that can be used to mount to the wheel force transducer as indicated in Figure 10. Figures 11 to 13 give detailed dimensions of these three mounting hole sets. In the case of the HMMWV, the modified rim is mounted to Hole Set 2 on the first flange. The hub is mounted to hole set 3 on the second flange via a hub adapter that goes through the inside of the wheel force transducer and maintains the correct rim offset. Hole set 1 in this case is used only to secure the outer dust cover. It is however recommended that Hole set 1 only be used for passenger vehicles due to the M8 bolts used here compared to the M10 bolts used for Hole sets 2 and 3.

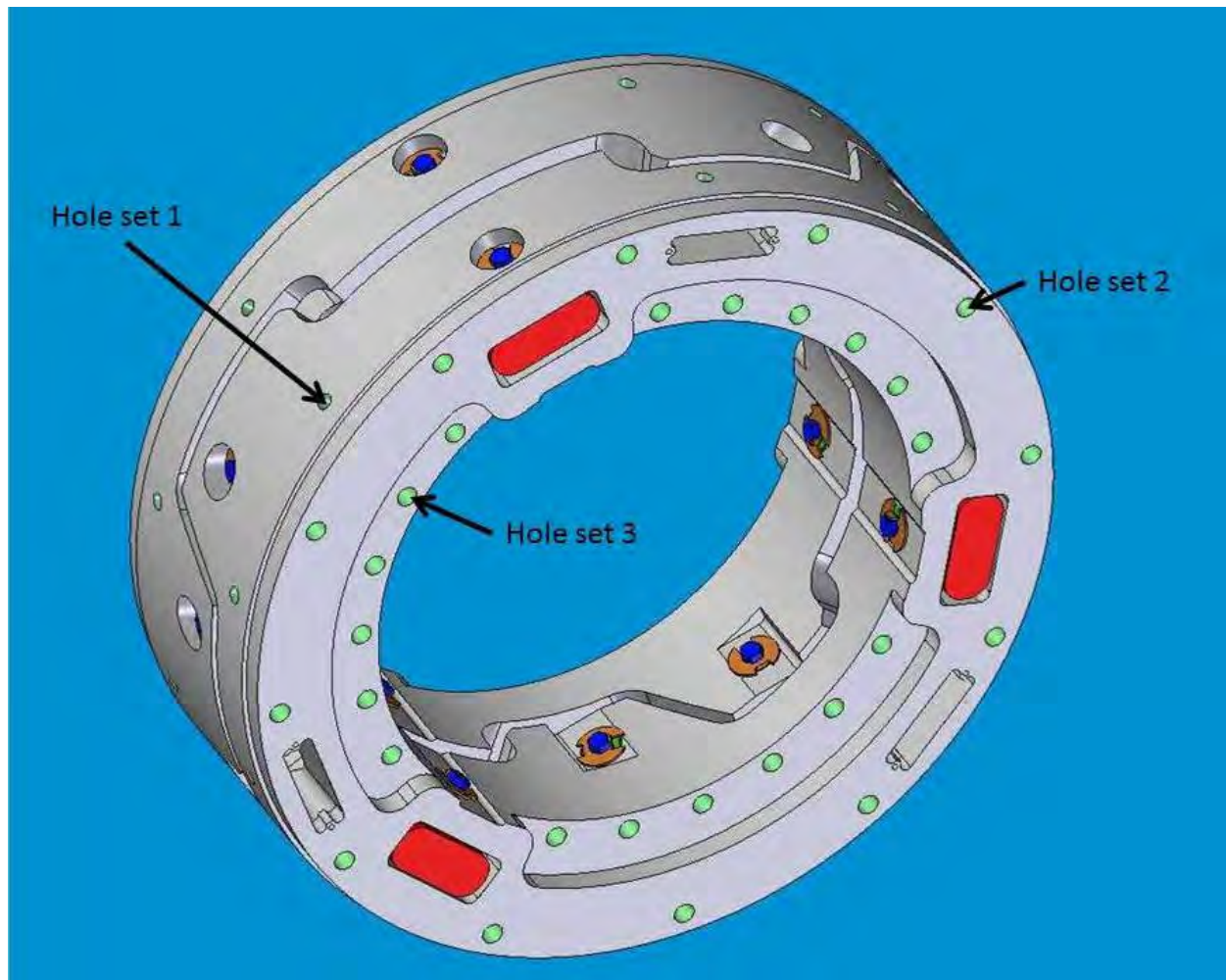


Figure 10 - Mounting hole options

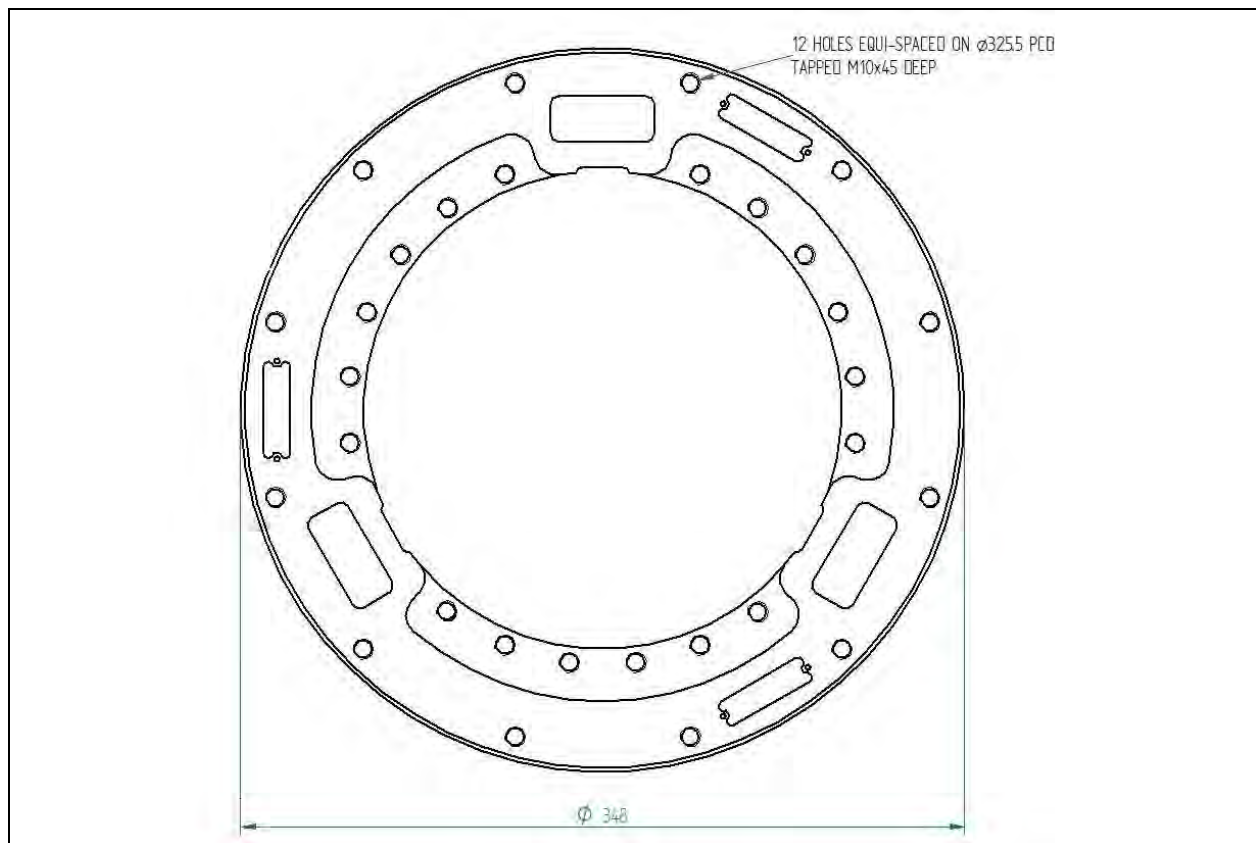


Figure 13 - Dimensions for Hole set 3

11. Research plans for remainder of the contract period.

A visit to CRELL is planned for mid 2012 to give feedback on the project progress and to discuss practical details of the project. We also plan to take our telemetry systems to CRELL and do some vehicle testing with them to evaluate the transducers and give them an opportunity to make an informed decision on the different telemetry options.

12. References

- [1] Proposal: Wheel force transducer development, 12 August 2010.
- [2] Contract W911NF-10-1-0463, awarded on 16 Sep 2010.
- [3] www.amgeneral.com/vehicles/hmmwv/expanded-capacity/details/m1165a1-with-b3, accessed 2010/11/02.
- [4] Wheel Force Transducer Research and Development, W911NF-10-1-0463, 1st Interim Report, September 2010 - December 2010, Prof. P.S. Els, University of Pretoria.
- [5] Wheel Force Transducer Research and Development, W911NF-10-1-0463, 2nd Interim Report, December 2010 – March 2011, Prof. P.S. Els, University of Pretoria.
- [6] Wheel Force Transducer Research and Development, W911NF-10-1-0463, 3rd Interim Report, – March 2011 – July 2011, Prof. P.S. Els, University of Pretoria.

13. Administrative actions

None.

14. Other important information

None.