LOCOSTRA: Blast-resistant Wheels Test

During May and June 2010, a series of comparative tests were conducted with four different designs of blast-resistant wheels built in the context of the LOCOSTRA (Low COSt TRActor) project. Tests took place in an open-air quarry named Valcena near Parma, Italy. These different types of charges containing 120g of Goma2Eco plastic explosive, 120g of TNT powder and 240g of TNT powder, respectively, were used in the tests.

The wheel prototypes were designed to resist physical damage and protect the vehicle on which they are mounted by consistently absorbing the resulting shockwaves caused by anti-personnel mine explosions. Because the wheels were developed with off-the-shelf material, they were simple and affordable. Moreover, they were designed for easy repair in local, nonspecialized workshops and, therefore, are appropriate for developing countries. The average cost of each wheel produced was 850€.

**Table 1. Wheels tested. All graphics courtesy of PMARlab.**

<table>
<thead>
<tr>
<th>Wheel no</th>
<th>Wheel Name (used only for reference in the text)</th>
<th>Description</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>All steel</td>
<td>Vented steel wheel</td>
<td>External diameter: 900mm Width: 235mm Weight: 85kg Steel thickness: 4mm</td>
</tr>
<tr>
<td>2</td>
<td>Florida</td>
<td>Embedding a small inflatable tire</td>
<td>External diameter: 900mm Width: 205mm Weight: 86kg Steel thickness: 4mm Inner wheel: inflatable tire wheel (trailer) with tube, external diameter of 500mm</td>
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<tr>
<td>3</td>
<td>EPR</td>
<td>Embedding a large inflatable tire</td>
<td>External diameter: 890mm Width: 250mm Weight: 160kg Steel thickness: 10mm Inner wheel: inflatable tire wheel (4WD vehicle) tubecel, external diameter of 750mm</td>
</tr>
<tr>
<td>4</td>
<td>Genoa</td>
<td>Embedding a solid rubber tire</td>
<td>External diameter: 865mm Width: 205mm Weight: 118kg Steel thickness: 4mm Inner wheel: solid rubber wheel (forklift truck), external diameter of 595mm</td>
</tr>
</tbody>
</table>
The global community is witnessing an increase in poor coun-
tries’ vulnerability to weather and economic volatility—in other words,
a decrease in their resilience. Resilience shares a strong link with in-
vestments in agricultural technologies, and the cause of decreasing re-
silience traces back to poor agricultural investments. While Africa’s in-
vestments in agricultural technologies are used as verification assets instead, a win-
win solution can be achieved by enhancing long-term development and
community resilience.

Blast-resistant Wheels

Each of the four wheels prototyped and tested was designed to with-
stand blast and to limit shockwave transfer to the relevant parts of the
vehicle to which the wheels are mounted. In particular, blast-resistant wheels
have been designed to:

- Withstand 240g of TNT and resist at least five explosions before
  maintenance is needed
- Keep the tractor safe by reducing the shockwave transmitted to the
  hull to harmless levels
- Be inexpensive
- Be easy to repair locally
- Have good traction
- Be lightweight

The four wheels are design variations of a concept intended to max-
imize shockwave and/or shockwave absorption via a flexible inner wheel, originally conceived by Andy Vian Smith, an active par-
ticipant in the design. Figure 1 on page 71 shows the four wheels with
their numbers and characteristics. Within the text of this article, wheels
are identified either by the dummy names or the numbers indicated in
Figure 1.

Test Method

The test aim was to compare the four designs and assess which wheel was
better at:

- Resisting physical damage
- Significantly reducing the energy transferred to the tractor

To measure the energy transferred, two sensors were employed: a
rotary encoder and a tri-axial accelerometer. The incremental encoder,
which was produced by Stegmann Inc., has a sensitivity of less than one-
thousandth of a degree. It was mounted on a ballistic pendulum (Figure 2),
designed to hold the wheels while they were subject to blast testing. The
pendulum was designed to have one degree of freedom with the pendu-
lar arm free to rotate around a joint sensorized with the encoder, which
was better at:

- Measuring the pendulum's angular displacement. The weight the pendu-

lum imposes on the pendulum’s arm is the weight of the pendulum.

The pendulum’s arm is the pendulum's arm that is being tested.

The four wheels were evaluated primarily on the ba-

Figure 2. Pendulum digital mock-up and prototype set-up before the test.

(US$1,187).1 The results from these comparative tests may be of great in-
terest to the mine-action community.

The Problem

The current global community is witnessing an increase in poor coun-
i tries’ vulnerability to weather and economic volatility—in other words,
a decrease in their resilience. Resilience shares a strong link with in-
vestments in agricultural technologies, and the cause of decreasing re-
silience traces back to poor agricultural investments. While Africa’s de-
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Due to the complexity of the science involved, there are numerous factors that
affect the energy transferred to the tractor hub during the test’s final phase, when the wheels that performed
the best were tested against a backdrop of TNT.

The tractor on which the LOCOSTRA is based is slightly modified to
host an industrial dual remote control. This means that no manual on-
board controls are modified or removed, and the operator can drive the
tractor or operate it remotely. The tractor is also equipped with light ar-
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of their ability to retain mechanical integrity after three consecutive blasts, with 120g of GomaZico, 120g of TNT and 240g of TNT respectively. Mechanical integrity was assessed in terms of:

- Loss of any wheel parts (including tread)
- Splitting or separation of material between welds
- Cracking or separation of welds
- Permanent deformation of steel parts
- Damage to rubber parts

As similar damage could be identified for each wheel, points were assigned to each particular impact and wheels scored on the basis of the sum of marks obtained. Wheels scoring fewer points were considered the best (Figure 6 above). For a clearer picture, Figure 6 sums up points scored by each wheel in all the three tests. In the case of a wheel also tested on the tractor, the worst point obtained between the pendulum and the tractor was considered.

Two wheels passed Phase 2 and therefore were also tested on the tractor during Phase 3. Those were wheel n. 3 (EPR) and wheel n. 4 (Genoa). Wheel n. 3 (EPR) was tested twice more—first against 120g of TNT and then against 240g of TNT. Wheel n. 4 (Genoa) was tested only once more against the manning charge, containing 120g of GomaZico plastic explosive.

From the point of view of deformation, wheel n. 5 (EPR) would be the best if it would not only deform. The deformation is particularly bad because it cannot be fixed in a workshop. Therefore, the best wheel turns out to be wheel n. 1 (All Steel), as it is less deformed. Next comes wheel n. 4 (Genoa) and then wheel n. 2 (Florida), which is the only wheel presenting separation of material. It has to be considered that wheel n. 3 (EPR) is 10mm thicker while all the others are 4mm thick.

All wheels survived at least three explosions without compromising their ability to turn. One (wheel n. 3) survived two more explosions, becoming very ovalized, and one (wheel n. 4) survived one more explosion but retained its ability to turn. Therefore, from the point of view of retaining mechanical integrity, all designs are promising and are worth investigating further.

Energy transferred. The second criterion used to evaluate wheel performance was the energy transferred. Energy was measured by two different means: by the encoder placed in the revolute joint between the pendulum arm and the pendulum base, and by the accelerometer placed within a flange mounted between the wheel and the hub on the pendulum as well as on the tractor.

The encoder measured the potential energy transferred from each wheel to the pendulum by measuring the pendulum arm’s maximum rotational displacement. Figure 7 on page 74 reports the maximum rotational displacement per wheel per explosion. To have a clearer and more general picture, Figure 7 sums up the maximum encoder values scored by each wheel in all the three tests. From this analysis, it can be said that wheel n. 4 (Genoa) transfers less potential energy than the other wheels. Therefore, a second general result is that, in the case of a blast-resistant wheel embedding rubber tire, the more and the softer the rubber, the better.

Figure 9 to the left, showing RMS values divided in two components acceleration in the vertical plane (x, y) and acceleration in the horizontal plane (z), illustrates another important fact: the presence in all cases of a high acceleration component along the accelerometer’s x-axis. This is unexpected since, when thinking about wheel design, focus on acceleration occurring along the x-axis is common, even though, according to our study, a high acceleration also occurs along the wheel axis. This result can be understood by examining the area of the surfaces exposed to explosions (Figure 10 on page 76). In fact, as the acceleration is proportional to the force and to the force transmitted to the surface it is applied to, multiplied by the pressure, the larger the surface, the higher the acceleration. In the case of the x and y axes, the geometric surface is large and because the geometry of the x-axis is large and because the geometry of the wheel and the relative position of the landmine and the wheel are never symmetrical, the acceleration along the x-axis is high.

Therefore, a third general result is that, when developing wheels to dissipate the shock wave associated with an explosion, it is worth concentrating also on acceleration dissipation along the z-axis, i.e., the wheel axis.

Conclusion

The main reason for this test was choosing which wheel out of four proposed designs was the best to mount on the LOCOSTRA. A large amount of data was recorded during the test, allowing for much analyzing and deep study.

After a long data processing period, analysis and ordering to achieve consistent results, wheel n. 4 (Genoa) was adopted (Figure 11 on page 76). The main reason behind this choice is the wheel’s good behavior among all evaluation criteria. In fact, although wheel n. 3 (EPR) performed better against higher quantities of explosive, as wheel n. 4 (Genoa) embeds a solid rubber tire, it dissipates energy by hysteresis cycles of the rubber, and a higher quantity of explosive acts on more rubber.

Inflatable inner wheels work well to absorb acceleration caused by small quantities of explosive, thanks to the large amounts of hysteresis cycles taking place into the rubber covering the inner wheel, due to the compression and expansion of the air inside (Figure 12); their ability to absorb acceleration caused by high-
the tractor.

or quantities of explosive is compromised by the limited amount of this rubber available.

4. All wheels are made out of tank heads, drilled and adapted to host the inner wheel. It would be more sustainable to use flat surfaces, i.e., standard steel profiles, which are widely available.

5. Using an inflatable 4WD vehicle tire as the inner wheel for the wheel n. 3 is a sound idea (thanks to Andy and Ed), because those tires are widely available.

6. The best blast-resistant wheel, on the basis of this test’s experience, is a wheel with a large, soft, rubber inner wheel, embedded into an outer rigid structure made of steel presenting the maximum possible number of holes to allow venting.

Profiling from lessons learned from the tests, Genoa’s design has been slightly modified. Wheels that are now mounted on the LOCOSTRA machine have been developed employing flat surfaces instead of tank heads. Moreover using slightly thicker steel—i.e., instead of mm—allowed fewer deformations. By keeping the same principle of joining the solid rubber inner wheel and the steel outer part, the best compromise between optimum outer wheel diameter, maximum venting and maximum shock absorption, related to the inner solid rubber wheel diameter, has been accounted for. A test on the same pendulum used on the first wheel produced confirmed that the measuring system used during the different tests has been reliable and the new wheel design has better behavior than the original wheel n. 4 (Genoa) design. After this last test, which occurred in November 2010 in the same location as the first test, LOCOSTRA was successfully tested against live anti-personnel landmines in Jordan during February and March 2011. There, with the support of the University of Jordan, the National Committee for Demining and Rehabilitation, Norwegian People’s Aid and the Geneva International Centre for Humanitarian Demining, LOCOSTRA was equipped with blast-resistant wheels designed according to lessons learned during the test described in this article, was driven over six live mines ranging from 29g of Tetryl (M14) to 240g of TNT, without registering any significant damage either on the wheels or on the machine itself.

Acknowledgements

These two tests have not taken place without the funding made available by the Italian Ministry of Economic Development, the Italian Institute of Foreign Trade and the Department of Mechanics and Machine Design of the University of Genoa, nor without the presence of every person who decided to join us and give us their time, not only in the quarry during the testing, but also at later events. Andy Vian Smith, Ed Pennington Ridge, Chris Chellingworth, Danilo Cappe, Cristina Pompini, Bela Fiorelli, Gianni Polentes, Andrea Polentes, Gil Emantara, Francesco Bagnoli and Paolino Bargigli Calvani. For their technical contributions, we would like to particularly thank Andy Vian Smith, Ed Pennington Ridge and Gil Emantara.

See endnotes page 83

Figure 10. Wheel surfaces hit by the blast wave. Blue is the surface perpendicular to x, y plane; red is the surface perpendicular to z axis.

Figure 11. Genoa wheel after the fourth explosion. Only this last test was done on the tractor.

Figure 12. Frames taken by the high speed camera during the explosion of 120g of TNT under Florida wheel. The upper part of the wheel moved 73mm upwards in 1/50s while the axis did not move.