Toward LOCOSTRA: Blast-resistant Wheels Test

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LOCOSTRA: Blast-resistant Wheels Test

Technical Survey, often an efficient method of achieving land release, can also be prohibitively expensive for certain communities due to the utilization of the same hulking, heavily-armored machines used in clearance operations. If Technical Survey could be achieved through the use of less expensive agricultural equipment that is already present in communities near suspected areas, land release could be achieved at a much lower price. The following study explores this possibility by examining the explosion resilience of four different designs of blast-resistant tractor wheels, each made of commercial off-the-shelf components and designed for easy reproduction in mine-affected communities.

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. Three 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>
<thead>
<tr>
<th>Wheel n°</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 Vented steel wheel</td>
<td></td>
<td>External diameter: 900mm Width: 235mm Weight: 85kg Steel thickness: 4mm</td>
</tr>
<tr>
<td>2</td>
<td>Florida Embedding a small inflatable tire</td>
<td></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>
</tr>
<tr>
<td>3</td>
<td>EPR Embedding a large inflatable tire</td>
<td></td>
<td>External diameter: 900mm Width: 250mm Weight: 106kg Steel thickness: 10mm Inner wheel: inflatable tire wheel (4WD vehicle) tubelss, external diameter of 750mm</td>
</tr>
<tr>
<td>4</td>
<td>Genoa Embedding a solid rubber tire</td>
<td></td>
<td>External diameter: 865mm Width: 205mm Weight: 118kg Steel thickness: 4mm Inner wheel: solid rubber wheel (fork-lift truck), external diameter of 595mm</td>
</tr>
</tbody>
</table>

Figure 1. Wheels tested. All graphics courtesy of PMARlab.
The "silence" traces back to poor agricultural investments. While Africa's decreasing in their resilience. Resilience shares a strong link with interest to the mine-action community. transmission. It has a double-steering system, is reversible, has a pow-
drive tractor to perform Technical Survey that is now sold at 50,000€.\textsuperscript{1} The results from these comparative tests may be of great interest.\textsuperscript{3} If ground-processing ag-
occurs, these machines are withdrawn from the field, and the area is treated with other more accurate methods.\textsuperscript{3} If ground in Technical Survey are the same employed for full clearance: expensive, heavily armored, highly powerful machines. As Techni-
clearance. The tractor on which the LOCOSTRA is based is slightly modified to
the pendulum was increased to a realistic value (approximately one-fourth
of the pendulum) and tested against 120g of Goma2E. (as wheels had slightly different weights, different counterweights were
used to achieve the desired weight) and tested against 120g of Goma2E
plastic explosive. During this first phase, the weight was kept to a low value to ensure an appreciable rotational displacement. This allowed re-
sources to compare wheel performance based on the amount of poten-
tial energy transferred. The encoder also recorded the pendulum arm's rotational displacements in subsequent tests, when the weight on the pendulum was increased to a realistic value (approximately one-fourth of the tractor weight).

During Phase 2, each wheel was mounted on the pendulum weighing 50kg (as wheels had slightly different weights, different counterweights were used to achieve the desired weight) and tested against 240g of TNT. In Phase 3, only the two wheels that performed best in previous phases were mounted on the tractor and tested; one against 240g of TNT and the other against 120g of Goma2E. Only one wheel was supposed to be tested on the tractor during Phase 3, in the field, how-
ever, two wheels performed well and it was decided to investigate both further. Before mounting the wheels on the tractor, the same sensorized flange hosting the tri-axial accelerometer used on the pendulum was mounted on the tractor hub.

Charges (Figure 4 to the left) were prepared in the field by filling plastic containers ranging 35mm-90mm in diameter with the explos-
ive required by the test phase. No covers were used, but, in the case of TNT, when containers were filled with TNT powder, Duct tape was used to secure some fabric firmly on top of the pressed powder. In order to increase reproducibility, a hole was dug into the thermalite arm, and a thermite block (Figure 3) filled in the hole above. Some gravel was placed on top and around the charge, closing the gap between the wheel and the charge. After each test, the thermite block was replaced with a new one. Two small wood pieces held the wheel on the thermite block at the required distance of 20mm from the top of the explosive. Charges were actuated by an electric detonator initiated remotely. After each explosion, each wheel was rotated in order to face the charge with a different part not yet deformed by previous explosions.

Phases: \textbullet~\textit{Phase 1}: Wheels were evaluated on the basis of their capability to retain me-
chanical integrity and to reduce the energy transferred to the tractor. Several findings resulted.\textbullet~\textit{Phase 2}: Wheels were evaluated primarily on the ba-
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 tested on the tractor during Phase 3. Those are 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 remaining charge, containing 120g of GomaZico plastic explosive.

From the point of view of deformation, wheel n. 3 (EPR) would be the best if it had not ever seen the explosion. The evaluation 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 (Garcia), which is the only wheel presenting separation of material. It has to be considered that wheel n. 3 (EPR) is 10mm thick 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 transfer (I). 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 cylindrical 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 global picture, Figure 7 sums up the maximum encoder values scored by each of the three tests. From this analysis, it can be said that wheel n. 4 (Genoa) transmits less potential energy than the other wheels.

Acceleration of a body is always proportional to the force applied to it. Therefore, by looking at the acceleration of the flange between the wheel and the pendulum or the tractor hub, wheels could be compared on the basis of their ability to reduce force transmitted to the tractor.

By processing data recorded by the accelerometer filtered at 500Hz (because frequencies higher than this value are not considered to cause mechanical vibrations), the root mean square values of acceleration (a sort of average value of the acceleration over time) for each wheel and for each explosive type and quantity was obtained (Figure 8 on page 76). To have a clearer picture, the RMS-values of acceleration for the same wheel in each of the three explosions were summed up. In the case of a wheel also tested on the tractor, the worst point obtained between the pendulum and the tractor was considered.

By examining the wheels’ behavior in each of the three explosions, it can be said that generally, wheel n. 4 (Genoa) transmits less acceleration than the other wheels, although the total RMS value is very similar to that of wheel n. 3. It can also be noticed that wheels embedded with an inflatable tire perform worse against higher quantities of explosive.

Additional results by observing the encoder values, wheel n. 1 (All Steel) performs well at transmitting little potential energy to the pendulum, being the second best wheel after wheel n. 4 (Genoa). Because the design of wheel n. 1 (All Steel) maximizes venting to the detriment of shock damping, a first general result learned is that ventilation helps reduce potential energy transfer.

When examining the total RMS acceleration values, wheel n. 4 (Genoa) performs 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 more rubbery.

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 (in the vertical plane (x, y) and in the horizontal plane (z)), illustrates another important fact: the presence in all cases of a high acceleration component along the accelerator’s z-axis. This is unexpected since, when thinking about wheel design, focus on acceleration occurring along the x plane 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 the force 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 surface is small and the pressure on the surfaces is low, while the surface is large and because the geometry of the wheel and the relative position of the landmine and the wheel are never symmetrical, the acceleration on the z-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.

Conclusions

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 similarly to wheel n. 4 in terms of energy dissipation, the wheel embedding rubber tire, due to the compression and expansion of the inner wheel, dissipates energy by hysteresis cycles of the rubber, and a higher quantity of explosive acts more rubbery.

Some important general considerations can be drawn from the tests and could be used in the future to approach new research into blast-resistant wheels:

1. Predictably, the wheel entirely made of steel has little deformation and transmits little potential energy (probably due to good venting), but transmits very high accelerations.

2. Some means of dispersing the force transmitted by the wheel along the z-axis should be considered.

3. Inflatable inner wheels work well to absorb acceleration caused by small quantities of explosive, thanks to the large amounts of hysteresis cycles taking place in 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...
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 machine itself.

Figure 12. Frames taken by the high speed camera during the explosion of 120g of TNT under Florida wheel.

Profiliting from lessons learned from the tests, Genoa’s design has been slightly modified. Wheels that are now mounted on the LOGOSTRA machine have been developed employing flat surfaces instead of tank heads. Moreover using slightly thicker steel—4mm instead of 3mm—allowed fewer deformations.

By keeping the same principle of having 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, LOGOSTRA 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 Genova International Centre for Humanitarian Demining, LOGOSTRA was equipped with blast-resistant wheels designed according to lessons learned during the test described in this article, was driven over six mine fields ranging from 29g of Tetryl (M16) to 240g of TNT, without registering any significant damage either on the wheels or on the machine itself.

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