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.

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Wheel n^0	**Wheel Name** (used only for reference in the text)	**Description**	**Characteristics**
1	All steel	Vented steel wheel	External diameter: 900mm Width: 235mm Weight: 85kg Steel thickness: 4mm
2	Florida	Embedding a small inflatable tire	External diameter: 900mm Width: 205mm Weight: 86kg Steel thickness: 4mm Inner wheel: inflatable tire wheel (trailer) with tube, external diameter of 500mm
3	EPR	Embedding a large inflatable tire	External diameter: 890mm Width: 250mm Weight: 161kg Steel thickness: 10mm Inner wheel: inflatable tire wheel (4WD vehicle) tubeless, external diameter of 750mm
4	Genoa	Embedding a solid rubber tire	External diameter: 865mm Width: 205mm Weight: 118kg Steel thickness: 4mm Inner wheel: solid rubber wheel (fork-lift truck), external diameter of 595mm

Figure 1. Wheels tested.
All graphics courtesy of PMARlab.

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€

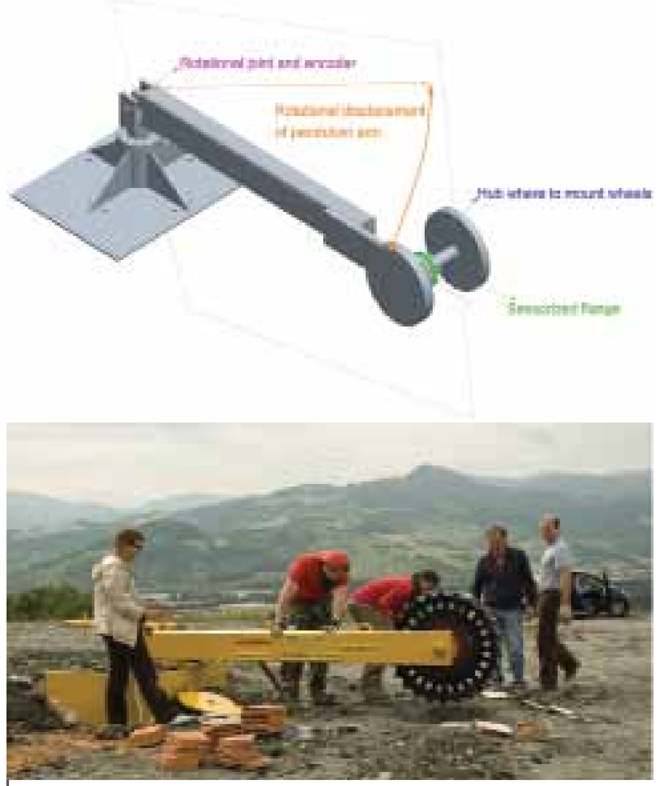


Figure 2. Pendulum digital mock-up and prototype set-up before the test.

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

The Problem

The global community is witnessing an increase in poor countries' vulnerability to weather and economic volatility—in other words, a decrease in their resilience. Resilience shares a strong link with investments in agricultural technologies, and the cause of decreasing resilience traces back to poor agricultural investments. While Africa's development aid has increased by 250% since the early 1980s, the allocation to agriculture has halved.[2] As the land's importance and value increases daily, releasing mine-suspected areas to local communities more quickly is increasingly necessary.

Luckily, many different countries are using Technical Survey to release land faster than in the past. While being quicker, though, the process is not inexpensive. Often, in fact, the machines used to process the ground in Technical Survey are the same employed for full clearance: expensive, heavily armored, highly powerful machines. As Technical Survey aims at verifying mine absence, machines used in Technical Survey are mainly employed on uncontaminated land. If an explosion occurs, these machines are withdrawn from the field, and the area is treated with other more accurate methods.[3] If ground-processing agricultural technologies are used as verification assets instead, a win-win solution can be achieved by enhancing long-term development and community resilience.

Within this context and upon these considerations, the LOCOSTRA project[4] started in November 2009. The project, ended in May 2011, led to the development of a low-cost machine based on a small four-wheel drive tractor to perform Technical Survey that is now sold at 50,000€ ($69,795). The tractor has a 79hp Deutz® diesel engine and a hydrostatic transmission. It has a double-steering system, is reversible, has a power takeoff and a standard three-point linkage system able to lift up to 1,800kg. Every kind of agricultural tool with standard three-point linkage attachment can be mounted on LOCOSTRA; until now it has been equipped with a mulcher, provided by FAE-Advanced Shredding Technologies and a ground-processing tool produced by NARDI – Agricultural Equipment. The machine has been equipped with a large loop detector donated by Ebinger and another agricultural-derived sweeping tool is under study at the University of Melbourne.

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 armoring composed of 3 mm-thick, steel deflection plates and new blast-resistant wheels.

This article presents results from a comparative test of four different designs of blast-resistant wheels made with commercial off-the-shelf components and designed for easy production in local workshops in mine-affected countries.

Blast-resistant Wheels

Each of the four wheels prototyped and tested was designed to withstand blasts 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 hub to harmless levels
- Be inexpensive
- Be easy to repair locally
- Have good traction
- Be lightweight

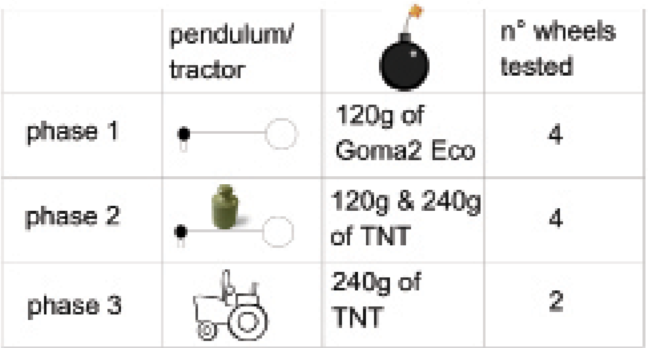
The four wheels are design variations of a concept intended to maximize shockwave venting and/or shockwave absorption via a flexible inner wheel, originally conceived by Andy Vian Smith, an active participant in the design. Figure 1 on page 71 shows the four wheels with their numbers and characteristics. 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-tenth 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 pendulum arm free to rotate around a joint sensorized with the encoder, which is able to measure its angular displacement. The weight the pendulum exerted on the wheel was adjusted by adding counterweights at the back of the pendulum. Each wheel was held firmly on the pendulum hub using bolts of the same diameter as those used on the LOCOSTRA. Between the wheel and the pendulum hub, a sensorized flange allowed for measurement of the hub's acceleration.



	pendulum/ tractor		n° wheels tested
phase 1		120g of Goma2 Eco	4
phase 2		120g & 240g of TNT	4
phase 3		240g of TNT	2

Figure 3. Test phases.

The encoder allowed the measurement of the energy transferred by each wheel by recording the pendulum arm's rotational displacement and, in particular, the maximum height reached by the arm during each explosion. The height reached is directly proportional to the energy transferred, because when the pendulum stops for an instant at the highest position, all its energy is in the form of potential energy.

The tri-axial accelerometer placed inside the flange was used to record hub acceleration. It was used on the pendulum as well as on the real tractor hub during the test's final phase, when the wheels that performed better on the pendulum were mounted on the tractor and tested in realistic conditions.

Acceleration is directly proportional to the force exerted on the hub by the blast wave. As the structure reacted, vibrating from the blast wave impulse, the recorded acceleration was oscillatory. In order to compare the wheels, data was processed to obtain the root mean square values of acceleration (a sort of average value of the acceleration over time), a value that measures the power of the blast wave passing through the wheel.

The accelerometer has sensitivity of 0.05mV/(m/s^2) and measurement range of 98,000m/s^2. The frequency range is 3–10,000Hz. It is tri-axial, and therefore allowed measurement of the acceleration components on the wheel plane and on the axis perpendicular to the plane.

A high-speed camera recorded a maximum of 20,000 fps in good lighting conditions and recorded the whole event, cross-checking the data obtained with other sensors. The other three cameras were traditional and recorded the explosions from different positions.

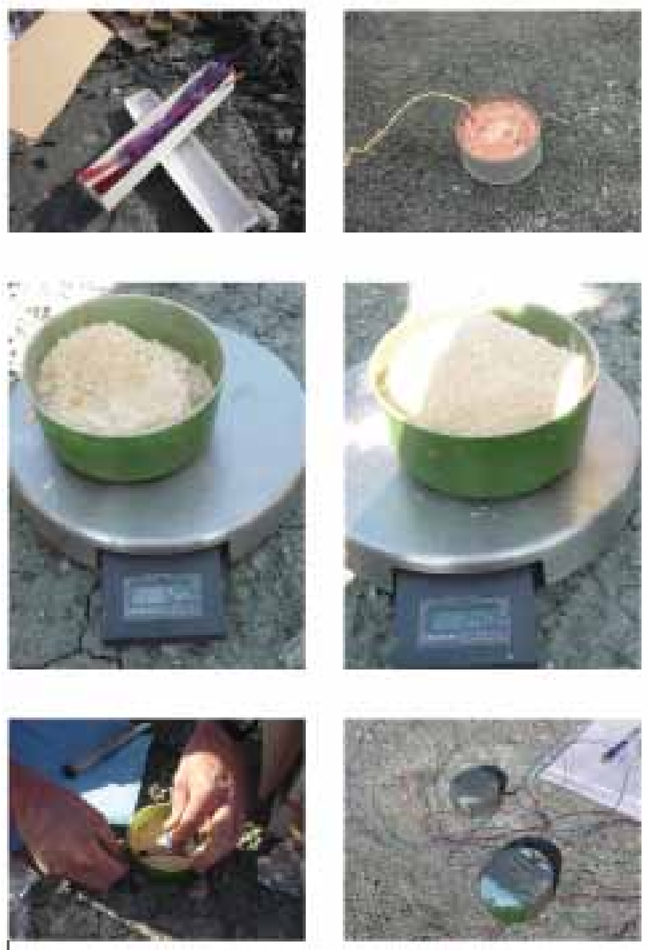


Figure 4. Charges.

The test was divided in three phases (Figure 3 on page 72). During Phase 1, each wheel was mounted on the pendulum weighing 250kg (as wheels had slightly different weights, different counterweights were used to achieve the desired weight) and tested against 120g of Goma2Eco plastic explosive. During this first phase, the weight was kept to a low value to ensure an appreciable rotational displacement. This allowed researchers to compare wheel performance based on the amount of potential 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 500kg (again, counterweights were employed) and tested first against 120g of TNT and later against 240g of TNT.

During 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 Goma2Eco. Only one wheel was supposed to be tested on the tractor during Phase 3; in the field, however, 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 explosive 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 under the pendulum arm, and a thermalite block (Figure 5) 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 thermalite block was replaced with a new one. Two small wood pieces held the wheel on the thermalite block at the required distance of 20mm from the top of the explosive.

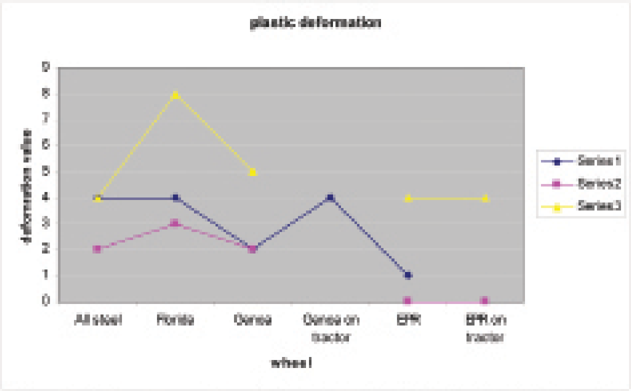
Charges were actuated by an electric detonator initiated remotely. After each explosion, each wheel was rotated in order to face the charge with a different part not yet deformed by previous explosions.

Results

Wheels were evaluated on the basis of their capability to retain mechanical integrity and to reduce the energy transferred to the tractor. Several findings resulted.

Mechanical integrity. Wheels were evaluated primarily on the ba-

Figure 5. Placement of the charge underneath the wheel and thermalite block.



Series1 is 120g of Goma2Eco, Series2 is 120g of TNT, Series3 is 240g of TNT

Wheel	Points (total)	Classification
All Steel	4+2+4=10	1
Genoa	4+2+5=11	2
Florida	4+3+8=15	3
EPR	1+0+4=5	4, due to ovalization

Figure 6. Results—mechanical integrity.

sis of their ability to retain mechanical integrity after three consecutive blasts, with 120g of Goma2Eco, 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

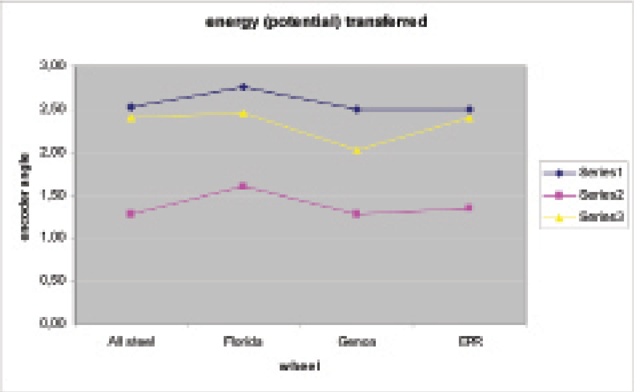
As similar damage could be identified for each wheel, points were assigned to each particular impact and wheels scored on the basis of the sum of marks obtained. Wheels scoring fewer points were considered the best (Figure 6 above). For a clearer picture, Figure 6 sums up points scored by each wheel 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. These 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 Goma2Eco plastic explosive.

From the point of view of deformation, wheel n. 3 (EPR) would be the best if it would not ovalize. The ovalization 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 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.

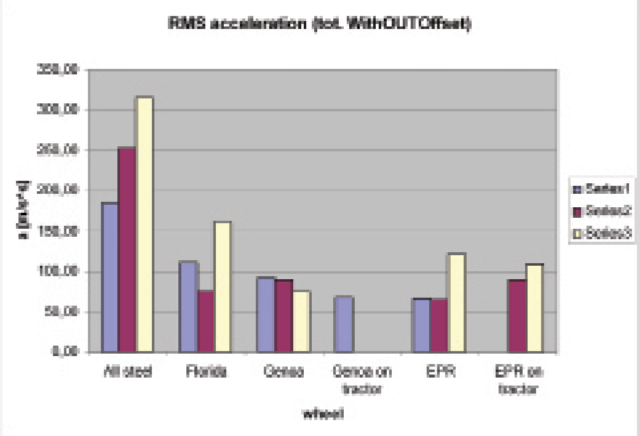
Energy transferred. The second criterion used to evaluate wheel performance was the energy transferred. Energy was measured by two different means: by the encoder placed in the revolute joint between the pendulum arm and the pendulum basis, and by the accelerometer placed within a flange mounted between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



Series1 is 120g of Goma2Eco, Series2 is 120g of TNT, Series3 is 240g of TNT

Wheel	Encoder value	Classification
All Steel	2.52+1.27+2.40=6.19	2
Genoa	2.50+1.27+2.02=5.79	1
Florida	2.75+1.60+2.46=6.81	4
EPR	2.50+1.34+2.40=6.24	3

Figure 7. Results—potential energy transferred.



Series1 is 120g of Goma2Eco, Series2 is 120g of TNT, Series3 is 240g of TNT

Wheel	Acc. RMS total value	Classification
All Steel	184.93+254.09+316.07=755.09	4
Genoa	92.77+90.22+74.98=257.97	1
Florida	110.45+75.15+161.79=347.39	3
EPR	66.32+89.86+121.65=277.83	2

Figure 8. Results—total RMS value of acceleration.

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 wheel in all 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.

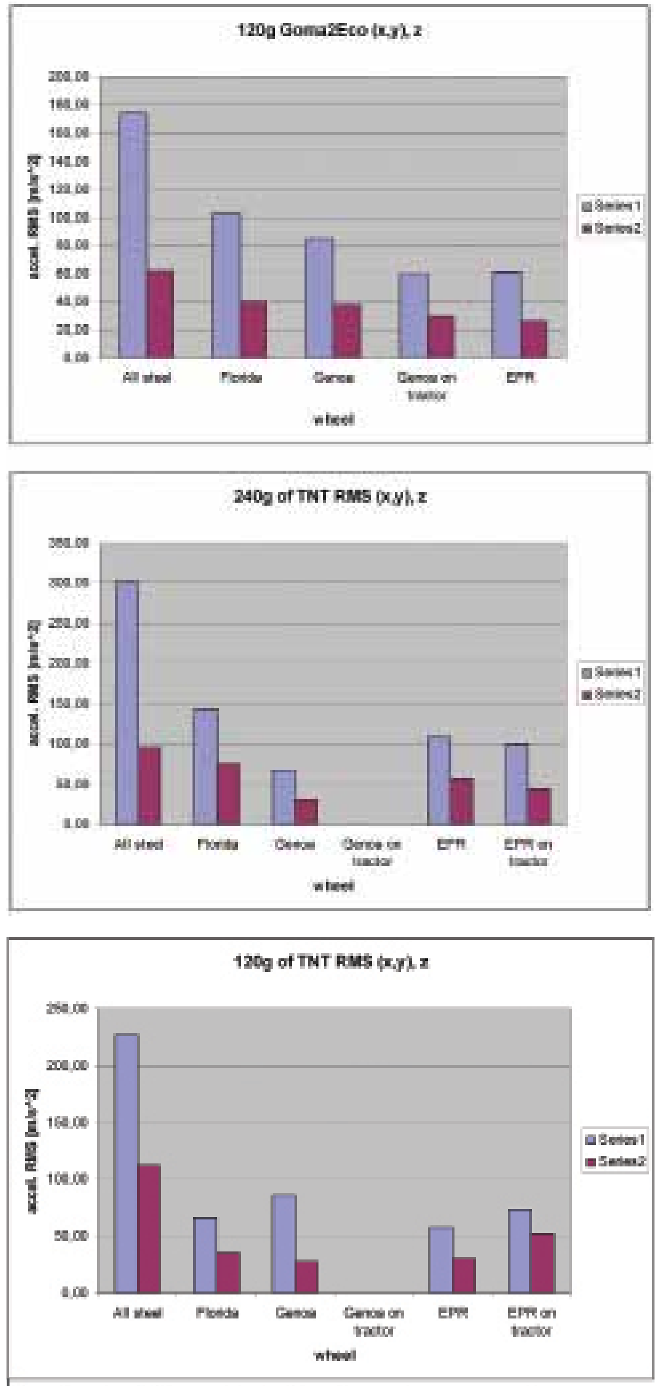


Figure 9. Components of RMS values of acceleration along in x,y plane and z axis.

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 74). 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 worst against higher quantities of explosive.

Additional results. By observing the encoder values, wheel n. 1 (All Steel) performs quite 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 dumping, 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 actuates more rubber.

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 z-axis. This is unexpected since, when thinking about wheel design, focus on acceleration occurring along the x,y 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 area exposed to explosions, perpendicular to the wheel plane, highlighted in blue in Figure 10, is not much larger than the surface of the wheel perpendicular to the z-axis, highlighted in red in Figure 10. Because this 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.

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 similarly to wheel n. 4 at reducing the acceleration transferred to the axis, it worked worst at dissipating potential energy and at retaining mechanical integrity.

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 dumping 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 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-

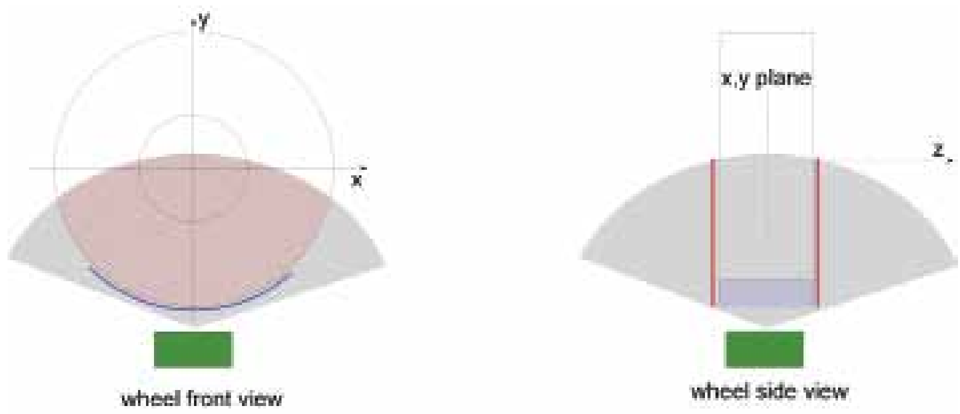


Figure 10. Wheel surfaces hit by the blast wave. Blue is the surface perpendicular to x, y plane; red is the surface perpendicular to z axis.

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.

er 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 these 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.

Profiting 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—6mm instead of 4mm—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, 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.

Acknowledgments

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