

# A NOVEL FACILITY FOR STATICALLY TESTING THE STABILITY OF VEHICLES: TECHNICAL FEATURES AND POSSIBILITIES

MARCO BIETRESATO\* & FABRIZIO MAZZETTO†

Libera Università di Bolzano, Facoltà di Scienze e Tecnologie – Fa.S.T., Bolzano, Italia

## ABSTRACT

The stability of a vehicle (especially if operating off-road, such as a farm tractor, possibly with an implement attached) can be statically investigated by means of a test installation such as the one described here. It consists of a platform (dimensions:  $6.42 \times 4.46$  m) having two degrees of freedom (inclination, rotation) and on which the vehicle is positioned motionless. By acting on these degrees of freedom, it is possible to precisely and simultaneously control all the characteristic angles of a vehicle (roll, pitch, yaw), thus discovering, in complete safety, its operational limits (i.e. its incipient rollover conditions). Furthermore, the ability to misalign up to two of the four quadrants composing the platform allows the testing of further critical situations for the vehicle, in which the front-axle pivot joint and the tyres elasticity are involved, potentially up to a scenario in which the vehicle rests on only three of its four supports and its support polygon degenerates into a triangle. The basic test scenarios that can be investigated with this installation allow the study of many aspects of a vehicle, pertaining both to the general chassis performance of the vehicle (therefore related to its balance) and to the load state of some specific components (internal or interfacing the vehicle with the outside, e.g. the wheels). The obtained data, referred to reference test scenarios, allow the experimenters to: (1) interpret sensors readings in real operating situations, thus including also the contribution of the tyres vertical flattening and lateral deflection, (2) complete the safety documentation at the users' disposal with some specific graphs, the vehicle 'equilibrium maps' (or 'stability charts'), possibly referred also to the vehicle with some accessories/implements connected to it. By demonstrating the undeniable usefulness of such an installation, the authors hope to propose new testing paradigms with the ultimate aim of increasing the overall safety of vehicles and, particularly, of agricultural and work machinery.

*Keywords:* Euler angles, rotating platform, stability on sloping grounds, stability test, tilting platform, turntable, vehicle overturning, vehicle rollover, vehicle stability.

## 1 INTRODUCTION

The *rollover* or *overturning* of vehicles, in particular of off-road machinery, such as agricultural and work machines, is a serious and, unfortunately, still widespread problem [1]–[7], with non-negligible and fatal consequences for drivers in most cases (up to 50%, as indicated by Mashadi and Nasrolahi [8]). Despite, over the years, legislators and manufacturers have certainly made an effort to establish clear test guidelines and build safer and safer machines, respectively, much still remains to be done on several fronts. In addition to spreading a safety culture among operators [9], which is a surely useful intervention, a very interesting point of work directly involves the *test systems and procedures*. Having the possibility of carrying out more comprehensive full-scale tests in a controlled (hence: safe) environment makes it possible to increase the knowledge about a vehicle in all its aspects [10], e.g. to precisely locate its Centre of Gravity (CoG) [11]–[13] and improve the physical-mathematical models underlying the static and dynamic behaviour of the vehicle even in the presence of elastic elements (such as: tyres and suspensions) and mobile subsystems (e.g. the front axle connected to the chassis with a pivot joint). This wider knowledge about the behaviour of machines can

---

\* ORCID: <https://orcid.org/0000-0002-6166-8958>

† ORCID: <https://orcid.org/0000-0001-9272-277X>

be primarily useful to set up novel active security systems to make a vehicle travel safely on sloping and harsh grounds [8], [14], possibly taking into account also the vehicle–terrain interaction [15], even in a fully-autonomously way [16].

At present, the test equipment used within the machinery homologation centres (e.g., the OECD test centres), as well as the test procedures implemented with such (standard) equipment, do not include any situation other than a *pure lateral* or a *pure longitudinal static rollover*. This means that a vehicle is tested motionless and its longitudinal axis is, respectively, perpendicular or aligned with the maximum slope direction, and the steering wheels are oriented as in a straight-ahead travelling configuration or, conversely, in a single specific steering configuration (in particular for all vehicles having an articulated frame with a central steering joint, such as telehandlers, pallet stackers, double stackers and order-picking trucks [17], [18]). The cited test scenarios (pure lateral/pure longitudinal rollover) foresee the control of *only the roll or the pitch angle, respectively* [19]–[21], being null the other Euler angles, as actually prescribed by international standards about static rollover of agricultural and work machinery [17], [18], [22], [23]. These scenarios have the clear advantage to require common equipment to be set up but represent only two very special conditions in which a vehicle can find itself. Some interesting proposals for unconventional test equipment for static rollover appeared only in research contexts, e.g.: a pre-fabricated spiral ramp [19], able to impose a vehicle on an increasing slope, or a four-post weighting test bench [24], able to calculate the static stability limits of a vehicle by using the static reactions at the wheels, measured by some load cells, as a function of the roll angle. On the other hand, there are only very few proposals of dynamic stability tests in the literature [14], [25]. Indeed, these are not covered by the standards, as they are difficult for the driver (necessarily on board) to perform safely.

Hence, starting from these prototypes, a novel installation, completely different from existing ones, unique in its design-concept and features [26], [27], was proposed to be installed in the ‘*Laboratory for Agroforestry Innovations*’ [28] of the Free University of Bolzano (Unibz), in Italy. Although very promising in its former theoretical testing capabilities (it would have been able to test even moving vehicles on it), for reasons of space, cost and safety, the initial design of the installation was then reduced to the most interesting and promising of its own subsystems, i.e. the ‘*turntable*’ [29]. So, it has been installed in the cited Laboratory for Agroforestry Innovations, and now it is ready to be used (Fig. 1). Therefore, the aim of this work is to present this novel test

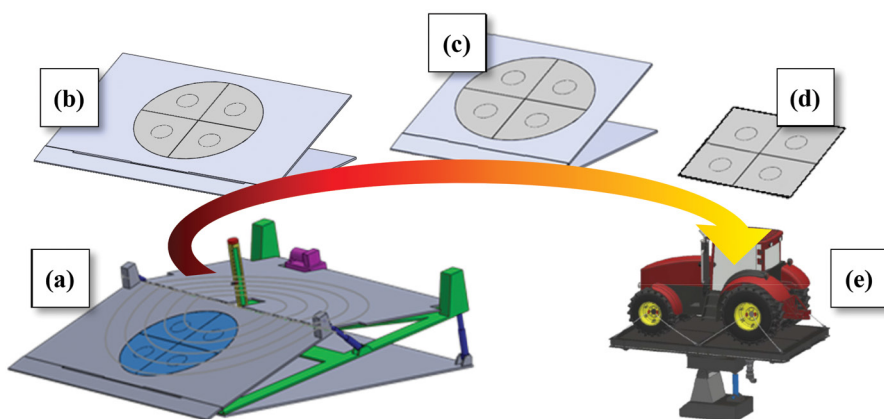


Figure 1: From (a) to (e): conceptual evolution of the design of the stability test installation; dimensions have been resized accordingly.

installation and its main technical features, describe the feasible test scenarios and illustrate the possible uses of the experimental data by the stakeholders (drivers, manufacturers and legislators).

## 2 TECHNICAL FEATURES OF THE TEST INSTALLATION

The test structure presented herein is basically composed of a sensorised, inclinable and rotary square platform (having dimensions:  $6.42 \times 4.46$  m; Fig. 2) used to support a motionless vehicle placed on it during the tests. Hence, this test structure, called, using a synecdoche, ‘turntable’ or ‘tilting platform’ or ‘rotating platform’ (hereinafter simply: ‘platform’), has two main degrees of freedom (Fig. 3), controlled by specific actuators, which are expressed in its ability to:

- tilt a support surface, capable of bearing the weight of an entire vehicle (up to a mass of 10,000 kg nominal, 15,000 kg maximum), by a set angle  $\alpha$  (up to  $55^\circ$ ) with respect to the horizontal plane (i.e. the plane on which the entire installation is anchored);
- rotate the above-said support plane by a known angle  $\beta$  (between  $0^\circ$  and  $360^\circ$ ) around an axis of rotation perpendicular to the vehicle support plane, which can therefore be tilted as described in the previous point.

The combination of these two rotations, one partial ( $\alpha$ , with respect to the horizontal plane; Fig. 4) and one complete ( $\beta$ , with respect to an inclinable rotational axis; Fig. 4), makes it possible to act simultaneously on the Euler angles (of: roll  $\varphi$ , pitch  $\vartheta$  and yaw  $\psi$ ) of the

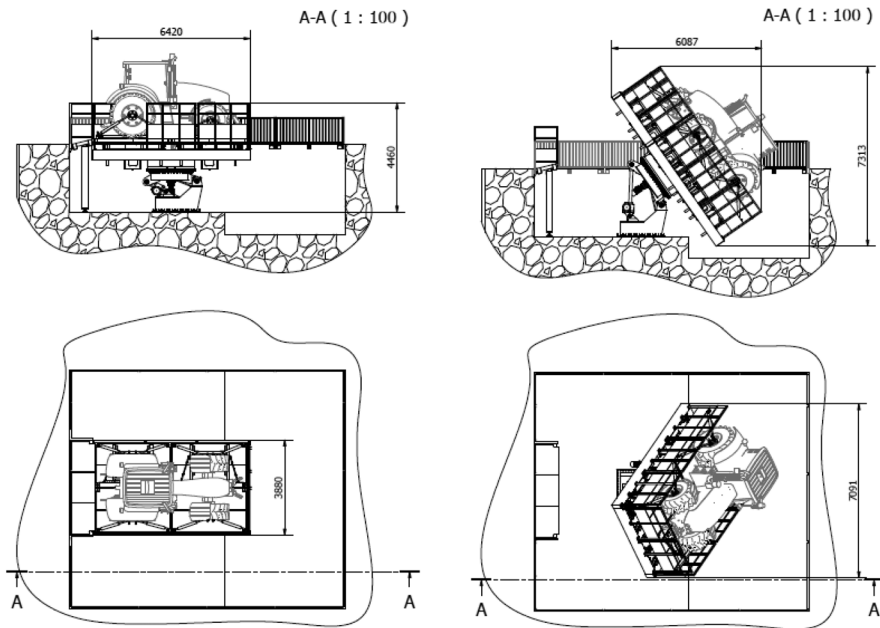


Figure 2: Orthogonal projections of the platform in a horizontal (pictures on the left) and inclined (pictures on the right) configuration; the reported maximum dimensions (in mm) were useful to define the position of the installation within the shed housing the Laboratory for Agroforestry Innovations at the Unibz.

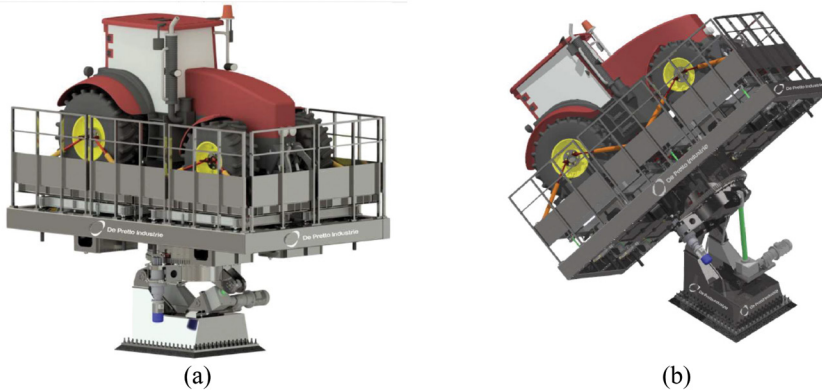


Figure 3: Renders of the 3D drawings of the platform; (a) platform in the horizontal configuration (assumed by the platform at the start/end of any test); (b) platform in a generic inclined and rotated configuration.

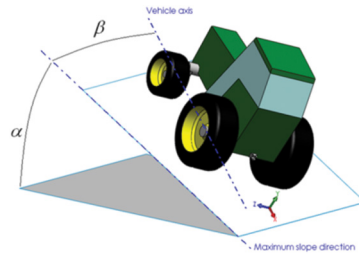


Figure 4: Vehicle (a farm tractor, in this case) having a generic inclination on a hillside [29], the two evidenced angles  $\alpha$  and  $\beta$ , imposed by the platform during the tests, impose specific angles of roll  $\varphi$ , pitch  $\vartheta$  and yaw  $\psi$  to the vehicle.

vehicle and, thus, to simulate any type of balance that the vehicle might experience along a hypothetical travel (upward or downward) on a slope (adapted from [29]):

$$\left\{ \begin{array}{l} \varphi = \arctan \frac{\sin \alpha \cdot \tan \beta}{\sqrt{1 + \cos^2 \alpha \cdot \tan^2 \beta}} \\ \vartheta = \arctan \frac{\sin \alpha}{\sqrt{\tan^2 \beta + \cos^2 \alpha}} \\ \psi = \arctan \frac{\tan \beta}{\cos \alpha} \end{array} \right. \quad (1)$$

For any further information on the possible outputs (e.g., graphs) and the mathematical relationships that allow the interpretation of the data, please refer to [29], which focuses only on these aspects.

The entire platform has a metal support surface with an anti-slip finish (Fig. 5). However, in order to prevent the vehicle from sliding downhill when it is tilted, special systems are used to lock the wheels in their initial position (so as the equivalent steel-rubber static friction coefficient can exceed 1 [30]), thus freeing the retention of the position from the pure-adherent weight. Indeed, by imposing a no side-slip situation (prescribed also by international standards), tests can be carried out in the most dangerous condition in which a vehicle can find itself, comparable to the presence of a step, by which the only possibility for the vehicle to reduce its potential gravitational energy is to rotate around the outer edge of the downstream tyres (hence: to overturn and not to slip along the slope).

The pit that surrounds the entire installation (Fig. 6) has two functions: (1) housing the load-bearing structure (having a height of 3.0 m at the vehicle support surface) so that the support plane for the vehicle, when horizontal, is aligned with the floor of the shed in which it is inserted; (2) allowing the tilting of the support plane, avoiding collisions with the concrete foundations. In addition, the pit itself is part of the platform safety system: if the vehicle were to become disengaged and, therefore, broke the anchorages, it would fall into the pit, stopping its motion and, thus, not compromising the surrounding structures. The experimenters, on the other hand, are safe inside a control room in an elevated position overlooking the platform (Fig. 7). During the tests, no other person needs to be present around the installation.

Another interesting feature of this installation is the possibility of vertically misaligning up to two quadrants at a time (Fig. 8). This creates interesting test scenarios where the support surface



Figure 5: Platform undergoing first tests after the final installation at the Laboratory for Agroforestry Innovations at the Unibz [31].

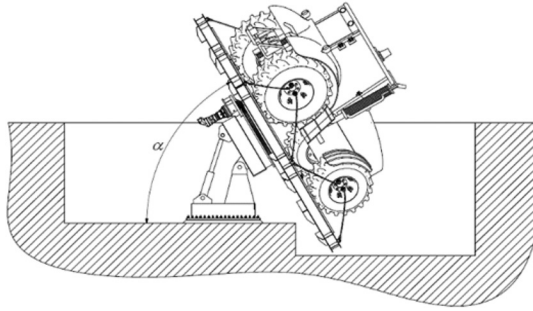


Figure 6: The pit (maximum depth 3.5 m at the right side of this drawing) allows the operation of the kinematic mechanism in charge of the inclination of the support platform; consequently, the connection of the load-bearing structure is under the shed floor to facilitate the initial positioning of the vehicle when  $\alpha = 0^\circ$ .



Figure 7: View of the platform and of its control cockpit from inside the control room in the Laboratory for Agroforestry Innovations at the Unibz [31].

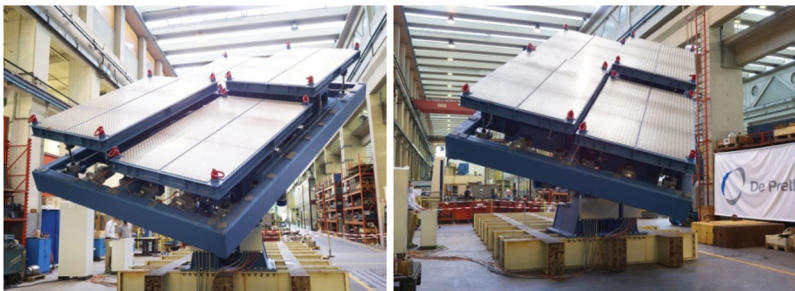


Figure 8: Platform undergoing final tests (inclination, rotation, alignment of quadrants) at the manufacturer's factory (De Pretto Industrie S.r.l., Schio, Vicenza, Italia [31], [32]) before the installation at the Unibz.

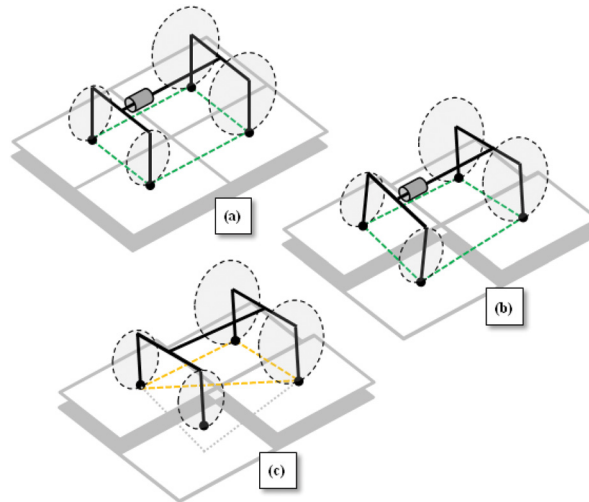


Figure 9: Possible scenarios occurring when two of the quadrants, initially aligned (a), are misaligned: if there is an unlocked pivot joint connecting the front and rear axles, the support polygon is still a quadrilateral (even if skew; in green) and all supports (wheels) touch the relative quadrants (b); otherwise, with no pivot joint, the support polygon degenerates into a triangle (in orange), due to a support not touching its quadrant (here: the front left wheel) (c).

is very similar to that experimented by a vehicle on a harsh surface or in an exit manoeuvre from an inter-row of a terraced slope [26] (Fig. 9): the elasticity of the tires and the possible presence of an unlocked pivot joint connecting the front axle to the chassis could or could not warrant the involvement of all the four supports (wheels) on the vehicle stability (Fig. 9). When only three supports remain to bear the vehicle weight, the support polygon, which normally is a quadrangle, degenerates into a triangle and possible rapid changes of the vehicle trim could happen at the increase of the platform inclination.

### 3 TEST POSSIBILITIES OFFERED BY THE INSTALLATION AND EXAMPLES OF USE OF TEST DATA

#### 3.1 Test scenarios viable with this test installation

Considering its technical features, illustrated above, the test installation can make a vehicle experiment three *basic test scenarios* (i.e.: *simple lateral tilt*, *simple longitudinal tilt* and *compound tilt*), which can be performed with all the quadrants aligned (and the vehicle under test surely laying initially on four supports) or with one or two quadrants misaligned (and the vehicle potentially laying initially on three supports only, as described before).

On the basis of the above-listed basic test scenarios, it is possible to experimentally inquire many aspects of a vehicle, basically related to the following *two main domains of relevance*:

1. the *general chassis performance of a vehicle*, i.e. including all aspects related to its balance on four or three supports, possibly considering also the sprung and unsprung masses of that vehicle and the presence of an agricultural implement or of other addi-

tional masses (CoG position, weight distribution and lateral/longitudinal incipient overturning angles);

2. the *load state of some specific components*, i.e. referred to some internal components or to the components interfacing the vehicle with the outside/surrounding environment, e.g. the wheels (and the related tyre flattening/lateral deflection), or the three-point hitch components, e.g. the top link and the lift arms, and the related stresses and strains.

### 3.2 Use of reference test scenarios to interpret sensor gatherings in real operative situations

By comparing the outputs of possible electronic sensors installed even after the vehicle construction, it is possible to establish a (bi-univocal) correspondence between some test scenarios, previously explored with this facility, and a generic situation experimented by a vehicle during its normal operation. Therefore, the results obtained at the test facility described here can be successfully exploited to make a vehicle safer also in its everyday use. For example, by using two inclinometers (or a single inertial measurement unit - IMU), at least two (ultrasound or optical) proximity sensors and a tyre pressure sensor per wheel, it is possible to study the *tyre flattening phenomenon*. Indeed, the inclinometers mounted on the chassis are useful to obtain the Euler angles for the vehicle chassis, the proximity sensors to obtain the actual distances of the chassis from the support plane (net of the surface roughness, if present;  $d_1$  and  $d_2$  in Fig. 10), the pressure sensors to measure the instant inflation pressure of the vehicle so as to modify accordingly the rollover safety limits for that vehicle after the execution of some tests at this installation.

This phenomenon is very interesting because it has two main effects on the vehicle stability, both complex and dangerous: on the one hand, it surely increases the inclination of the chassis and shifts the CoG down the slope [34], on the other hand, it modifies the width of the support polygon due to the associated lateral lying down of the downstream tyre [35]. Therefore, the maximum guard angle (i.e. tolerable to keep the vehicle safe) decreases as the tyres inflation pressure decreases. The same angle can also be corrected in case of individual tyres with different inflation pressures, as in the case of a puncture.

Since these reference situations were previously inquired on the test installation and the weight supported by each quadrant (hence: by each vehicle wheel) was accurately measured,

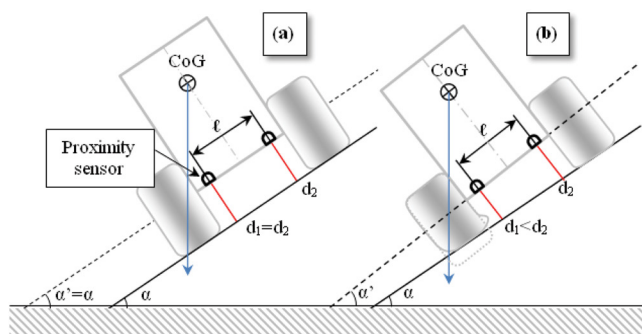


Figure 10: Lateral inclination in an ideal (a) and real (b) situation; in (b) the tyre flattening phenomenon, occurring mostly at the downstream tyres, increases the lateral inclination of the vehicle chassis ( $d_1 < d_2 \rightarrow \alpha' > \alpha$ , where  $\alpha'$  is, in this case, the vehicle roll angle  $\varphi$ ), thus making the CoG projection reach the edge of the support polygon (i.e. an incipient overturning condition; see also [33]).



it is possible to inferentially determine the instantaneous position of the vehicle CoG in any real situation by using the previously-collected experimental data (hence, true and not theoretical). Consequently, the residual safety margin at rollover in various slope and tyres inflation situations can also be determined. The lower the tyres inflation pressure, the lower the corresponding equivalent elastic constant (thus including both the carcass and the inflation air [34]) and the greater the tyres compliance with load transfers.

### 3.3 Use of reference test scenarios to complete the safety documentation at the users’ disposal

When the position of a vehicle CoG is known from the tests carried out, it is possible, for a manufacturer of agricultural machinery, to include in the owner’s manual a series of specific graphs, the so-called vehicle ‘*equilibrium maps*’ (or ‘*stability charts*’), which are also useful for training the users/drivers in dedicated safety/training courses (e.g., for letting them obtain a specific driving licence). These equilibrium maps, presented in a previous publication [36], are very similar to the graphs usually provided with cranes, telescopic mobile cranes and forklift elevators, called ‘*load lift charts*’ or ‘*load diagrams*’ or ‘*range diagrams*’ (Fig. 11). These charts relate the boom outreach to the maximum payload that can be lifted without tipping or structural failure and, therefore, indicate the safety operating conditions of these machines. In these cases, different colours are related to different ranges of payloads mass that can be lifted.

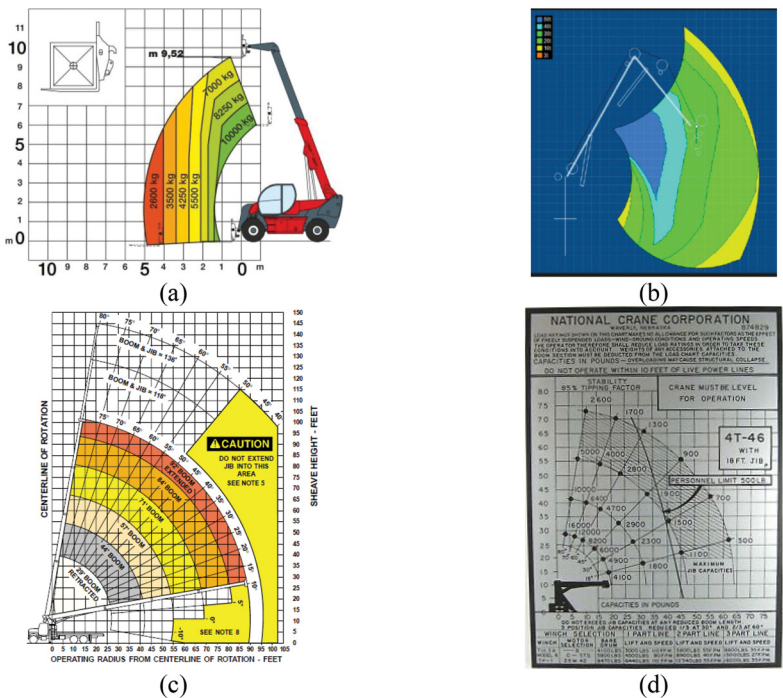


Figure 11: (a) Load chart for a ‘Magni HTH 10.10’ forklift machine [38]; (b) example of a load chart for a crane generated by a simulator [39]; (c) range diagram for a ‘Terex BT5092’ mobile crane [40]; (d) load lift chart plate for a ‘National 4T46’ crane, applied to its cockpit for easy reference [41].

In the case under study, instead, the stability maps would allow the reader to graphically calculate, using the usual traffic light colours, the condition of stability or danger of a vehicle and, in case of a farm tractor, also with any agricultural implement connected to its front, rear or side (Fig. 12). The stability condition can be quantified by using a proper metric, such as the Roll Stability Index (RSI), spanning from 0 to 1 (or from 0% to 100%): when the RSI reaches zero, the vehicle is in a situation of incipient overturning [11], [37], meaning that the direction of the resultant of the active forces applied to the CoG intersects the support polygon close to (or on) the edge of the support polygon ('*stability condition of a spatial structure or of a vehicle on a ground*' [33]). The quantities of interest to be reported on the axes of the stability maps can be related to the *environmental conditions* (slope angle  $\alpha$ , turning radius R) or, only if dealing specifically with a farm tractor, to the *features and conditions of operation/connection for an implement* (implement mass M, height of the implement CoG above the supporting plane H, distance between the implement CoG from the rear axle L). An example is visible in Fig. 12.

The equilibrium maps for farm tractors, which would be proposed after the tests at the platform, specific to each individual vehicle, would then be associated also with each category of *mounted implements*, i.e. which stay above the ground during their operation (meaning that their weight is completely supported by the tractor; Table 1; Figs. 13–15).

There is also the experimental possibility of generating such equilibrium maps directly from the specific implements already available to the owner of the vehicle under test (instead of from generic mock-up masses), which is a very interesting possibility for owners [10]. The equilibrium maps should be consulted before the tractor is connected to an implement in order to be aware of the overturning limits, which are different from those of the tractor on its own, and perhaps to set different visual and acoustic alarms for tilting (if present). The same equilibrium maps can also exist in a completely digital format so that:

- they can be consulted interactively via a notepad/smartphone when necessary, or
- they can also be recalled on the vehicle on-board screens, provided that there is a system for the automatic recognition of the connected implement.

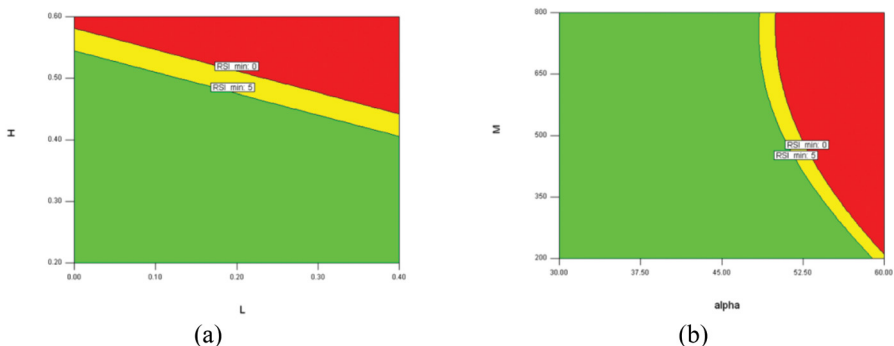


Figure 12: Examples of equilibrium maps for a farm tractor showing: (a) the effect, on the RSI, of the CoG position ( $x$  axis: L;  $y$  axis: H) of a rear implement having a mass  $M = 200$  kg ( $\alpha = 45^\circ$ ,  $R = 2$  m); (b) the effect, on the RSI, of the ground slope  $\alpha$  ( $x$  axis) and of the mass  $M$  ( $y$  axis) of an implement ( $H = 0.2$  m,  $L = 0.2$  m,  $R = 2$  m); the colours indicate a condition of *safety* (green;  $RSI > 5$ ), *attention* (yellow;  $0 \leq RSI \leq 5$ ) and *danger* (red;  $RSI < 0$ ) for the tractor [36].

Table 1: Categorization of mounted agricultural implements (adapted from [36]).

	Scenario of reference/category of implement	Examples of implement
1	Tractor with an implement mounted at the front/rear and operating centrally with respect to the tractor longitudinal axis; the connection of the implement to the tractor is made through a properly designed front/rear lifter equipping the tractor	Front shredder/fodder cutter/vine-shoot shredder/loader; tillage implements when not in operation (i.e. during transfers); slurry mixer; mounted boom sprayer/mistblow sprayer
2	Tractor with an implement mounted at the front/rear and operating laterally/not centrally with respect to the tr. longitudinal axis; the implement is at the external/internal side of the turn; the connection of the implement to the tr. is made through a properly designed front/rear lifter	Lateral shredder/fodder cutter; unilateral/bilateral shoot remover; single/double sickle bar; backhoe
3	Tractor with an implement positioned directly on the tractor front/rear end, i.e. on a plane above the front/rear axle (NB: only for tractors having an integrated loading bay next to the cabin, e.g. implement-carriers/multi-purpose tractors)	Sprayer equipment; tipper body



Figure 13: Examples of implements belonging to scenario/category 1 of Table 1; (left) front shredder [42]; (right) mounted mistblow sprayer [43].



Figure 14: Examples of implements belonging to scenario/category 2 of Table 1; (left) lateral shredder [44]; (right) single sickle bar [45].



Figure 15: Examples of implements belonging to scenario/category 3 of Table 1; (left) ‘Claas Xerion Saddle Trac’ multi-purpose tractor with slurry tanker equipment on the rear axle [46]; (right) ‘Fendt F 345 GT’ implement carrier with a tipper body on the front axle [47].

#### 4 CONCLUSIONS

A novel facility to test the stability of vehicle has been presented here and its main technical features have been described. Thanks to a set of basic test scenarios, it allows performing many experimental investigations concerning both the general chassis performance of a vehicle and the load state of specific components of its. The data that can be collected can be used in many ways, e.g. to correctly interpret the gatherings of some on-board sensors in real operative situations or to complete the safety documentation at the users’ disposal via some specific charts, the ‘equilibrium maps’. Albeit the authors are aware that much work needs to be done in terms of disseminating a safety culture among operators, they hope that this test installation will make an effective contribution to improving the safety of agricultural machinery, which has always been critical.

#### ACKNOWLEDGEMENTS

This study was developed within the activities foreseen by the ‘*Alpine Technologies*’ contract for research capacity building (‘ALPItec’) of the Free University of Bolzano, grant number TN820A, funded by the Autonomous Province of Bolzano/Bozen [48].

The authors wish to thank Ing. Diego Ruaro of De Pretto Industrie S.r.l. [32] for the iconographic material about the test installation put at their disposal.

#### REFERENCES

- [1] Liu, J. & Ayers, P.D., Off-road Vehicle Rollover and Field Testing of Stability Index. *Journal of Agricultural Safety and Health*, **5(1)**, pp. 59–72, 1999. DOI: 10.13031/2013.5700.
- [2] Goldenhar, L.M. & Schulte, P.A., Methodological issues for intervention research in occupational health and safety. *American Journal of Industrial Medicine*, **29(4)**, pp. 289–294, Apr. 1996. DOI: 10.1002/(SICI)1097-0274(199604)29:4<289::AID-AJIM2>3.0.CO;2-K.
- [3] Yoder, A.M. & Murphy, D.J., Evaluation of the Farm and Agricultural Injury Classification Code and follow-up questionnaire. *Journal of Agricultural Safety and Health*, **6(1)**, pp. 71–80, Feb. 2000. [Online]. Available: <http://www.ncbi.nlm.nih.gov/pubmed/10938754>.
- [4] Hallman, E.M. & Pollock, J., Learning from tragedy: How to effectively perform and utilize an injury investigation - Paper No. 997045’, *ASAE*, 1999.

- [5] Cecchini, M., Cossio, F., Marucci, A., Monarca, D., Colantoni, A., Petrelli, M. & Allegrini, A., Survey on the status of enforcement of European directives on health and safety at work in some Italian farms. *Journal of Food, Agriculture and Environment*, **11(3&4)**, pp. 595–600, 2013. [Online]. Available: [http://world-food.net/download/journals/2013-issue\\_3&4/2013-issue\\_3&4-\\_food/f117.pdf](http://world-food.net/download/journals/2013-issue_3&4/2013-issue_3&4-_food/f117.pdf).
- [6] Váliková, V., Rédl, J., & Antl, J., Analysis of accidents rate of agricultural off-road vehicles. *Journal of Central European Agriculture*, **14(4)**, pp. 1303–1316, 2013. DOI: 10.5513/JCEA01/14.4.1348.
- [7] Fagnoli, M. & Lombardi, M., Safety vision of agricultural tractors: an engineering perspective based on recent studies (2009–2019). *Safety*, **6(1)**, p. 1, Dec. 2019. DOI: 10.3390/safety6010001.
- [8] Mashadi, B. & Nasrolahi, H., Automatic control of a modified tractor to work on steep side slopes. *Journal of Terramechanics*, **46(6)**, pp. 299–311, Dec. 2009. DOI: 10.1016/j.jterra.2009.08.006.
- [9] Murphy, D.J., Kiernan, N.E. & Chapman, L.J., An occupational health and safety intervention research agenda for production agriculture: does safety education work? *American Journal of Industrial Medicine*, **29(4)**, pp. 392–6, Apr. 1996. doi: 10.1002/(SICI)1097-0274(199604)29:4<392::AID-AJIM23>3.0.CO;2-W.
- [10] Spencer, H.B., Owen, G.M. & Glasbey, C.A., On-site measurement of the stability of agricultural machines. *Journal of Agricultural Engineering Research*, **31(1)**, pp. 81–91, Jan. 1985. DOI: 10.1016/0021-8634(85)90126-X.
- [11] Vidoni, R., Bietresato, M., Gasparetto, A. & Mazzetto, F., Evaluation and stability comparison of different vehicle configurations for robotic agricultural operations on side-slopes. *Biosystems Engineering*, **129**, pp. 197–211, 2015. DOI: 10.1016/j.biosystemseng.2014.10.003.
- [12] Mazzetto, F., Bietresato, M., Gasparetto, A. & Vidoni, R., Simulated stability tests of a small articulated tractor designed for extreme-sloped vineyards. *Journal of Agricultural Engineering*, **XLIV(s1)**, pp. 663–668, 2013. doi: 10.4081/jae.2013.(s1):e133.
- [13] Majdan, R., Abrahám, R., Kollárová, K., Tkáč, Z., Matejková, E. & Kubík, E., Alternative models for calculation of static overturning angle and lateral stability analysis of subcompact and universal tractors. *Agriculture*, **11(9)**, p. 861, Sep. 2021. DOI: 10.3390/agriculture11090861.
- [14] Bietresato, M., Belotti, R., von Ellenrieder, K.D. & Mazzetto, F., A preliminary study of active stabilization for agricultural machines using a movable mass. Nov. 2019. DOI: 10.1115/IMECE2019-11507.
- [15] Bekker, M.G., *Theory of Land Locomotion: The Mechanics of Vehicle Mobility*. USA: The University of Michigan Press, 1956.
- [16] Peters, S.C. & Iagnemma, K., An analysis of rollover stability measurement for high-speed mobile robots. in *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.*, pp. 3711–3716, DOI: 10.1109/ROBOT.2006.1642269.
- [17] UNI ISO, ‘UNI ISO 22915-4:2012 Carrelli industriali - Verifica della stabilità - Parte 4’, 2012.
- [18] UNI EN, ‘UNI EN 1459-3:2015 Carrelli elevatori fuoristrada - Requisiti di sicurezza e verifica - Parte 3’, 2015.
- [19] A. J. Scarlett, J. N. Reed, D. A. Semple, P. C. Seward, A. D. Stockton, and J. S. Price, Operator roll-over protection on small vehicles - Research Report 432. Silsoe, United

- Kingdom, 2006. Accessed: May 24, 2013. [Online]. Available: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Operator+roll-over+protection+on+small+vehicles#0>.
- [20] Zhao, X.T., Jiang, H.Z., Zheng, S.T. & Han, J.W., Precision gravity center position measurement system for heavy vehicles. *Key Engineering Materials*, **315–316**, pp. 788–791, 2006. DOI: 0.4028/www.scientific.net/KEM.315-316.788.
- [21] Franceschetti, B., Lenain, R. & Rondelli, V., ‘Comparison between a rollover tractor dynamic model and actual lateral tests’, *Biosystems Engineering*, **127**, pp. 79–91, Nov. 2014, doi: 10.1016/j.biosystemseng.2014.08.010.
- [22] ISO, ‘ISO 16231-2:2015 - Self-propelled agricultural machinery - Assessment of stability - Part 2: Determination of static stability and test procedures’, 2015.
- [23] ISO, ‘ISO 789-6:1982 - Agricultural tractors - Test procedures - Part 6: Centre of gravity’, 1982.
- [24] Gravalos, I., Gialamas, T., Loutridis, S., Moshou, D., Kateris, D., Xyradakis, P. & Tsiropoulos, Z., An experimental study on the impact of the rear track width on the stability of agricultural tractors using a test bench. *Journal of Terramechanics*, **48(4)**, pp. 319–323, Aug. 2011. DOI: 10.1016/j.jterra.2011.04.003.
- [25] S. Popescu and N. Sutru, Contributions to the study of the dynamics of agricultural tractors equipped with front-end loader and rear forklift loader. in *Engineering for Rural Development - International Scientific Con*, 2009. pp. 165–170, Accessed: May 06, 2013. [Online]. Available: <http://www.cabdirect.org/abstracts/20093261569.html>.
- [26] Bietresato, M. & Mazzetto, F., Definition of the layout for a new facility to test the static and dynamic stability of agricultural vehicles operating on sloping grounds. *Applied Sciences*, **9(19)**, p. 4135, Oct. 2019. DOI: 10.3390/app9194135.
- [27] Bietresato, M. & Mazzetto, F., Increasing the safety of agricultural machinery operating on sloping grounds by performing static and dynamic tests of stability on a new-concept facility. *International Journal of Safety and Security Engineering*, **8(1)**, pp. 77–89, Jan. 2018. DOI: 10.2495/SAFE-V8-N1-77-89.
- [28] Noi Spa, Agroforestry Innovations Lab. 2021. <https://noi.bz.it/en/agroforestry-innovations-lab>.
- [29] Bietresato, M. & Mazzetto, F., Stability tests of agricultural and operating machines by means of an installation composed by a rotating platform (the ‘turntable’) with four weighting quadrants. *Applied Sciences*, **10(11)**, p. 3786, May 2020. DOI: 10.3390/app10113786.
- [30] van Beek, A., Coefficient of friction, Rolling resistance and Aerodynamics. *Advanced engineering design - Lifetime performance and reliability*, 2019. <https://www.tribology-abc.com/abc/cof.htm>.
- [31] De Pretto Industrie S.r.l., De Pretto Industrie - Test Benches for Vehicles. <https://www.deprettoindustrie.com/mechanical-testing-systems/>.
- [32] De Pretto Industrie S.r.l., De Pretto Industrie - Energy Industry solutions. 2021. <https://www.deprettoindustrie.com/>.
- [33] Bietresato, M. and Mazzetto, F., Morphometry as a key to investigate the stability to a wind-induced rollover of agricultural equipment for irrigation. *International Journal of Safety and Security Engineering*, **10(1)**, pp. 129–139, Feb. 2020. DOI: 10.18280/ijssse.100117.
- [34] Anifantis, A.S., Cutini, M. & Bietresato, M., An Experimental–Numerical Approach for Modelling the Mechanical Behaviour of a Pneumatic Tyre for Agricultural Machines. *Applied Sciences*, **10(10)**, p. 3481, May 2020. DOI: 10.3390/app10103481.

- [35] Majdan, R., Abrahám, R., Tkáč, Z., Drlička, R., Matejková, E., Kollárová, K. & Mareček, J., Static lateral stability of tractor with rear wheel ballast weights: comparison of ISO 16231-2 (2015) with experimental data regarding tyre deformation. *Applied Sciences*, **11**(1), p. 381, Jan. 2021. DOI: 10.3390/app11010381.
- [36] Bietresato, M., Carabin, G., Vidoni, R., Mazzetto, F., & Gasparetto, A., A parametric approach for evaluating the stability of agricultural tractors using implements during side-slope activities. *Contemporary Engineering Sciences*, **8**(25–28), pp. 1289–1309, 2015. DOI: 10.12988/ces.2015.56185.
- [37] Mazzetto, F., Bietresato, M., & Vidoni, R., Development of a dynamic stability simulator for articulated and conventional tractors useful for real-time safety devices. *Applied Mechanics and Materials*, **394**, pp. 546–553, 2013. DOI: 10.4028/www.scientific.net/AMM.394.546.
- [38] LiftEquipt, 10.10 Family Technical Specifications. 2021. <https://liftequipt.com.au/magni/magni-hth/magni-hth-10-10/>.
- [39] Bye, R.T., Osen, O.L. & Pedersen, B.S., A Computer-Automated Design Tool For Intelligent Virtual Prototyping of Offshore Cranes. in *ECMS 2015 Proceedings*, eds. V.M. Mladenov, P. Georgieva, G. Spasov & G. Petrova, May 2015. pp. 147–156, DOI: 10.7148/2015-0147.
- [40] Giuffre Bros. Cranes Inc., Terex BT5092. 2015. <https://giuffre.com/terex-bt5092-load-chart>.
- [41] eBay Inc., National Crane 4T46 Load Lift Chart Plate. 2021. [https://www.ebay.com.au/itm/National-Crane-4T46-Load-Lift-Chart-Plate-/254663113941?\\_trkparms=aid%3D1110006%26algo%3DHOMESPLICE.SIM%26ao%3D1%26asc%3D20160323102634%26meid%3D7d37170c6b8e4c64a846c3b88bd55fe6%26pid%3D100623%26rk%3D2%26rkt%3D5%26sd%3D32441047](https://www.ebay.com.au/itm/National-Crane-4T46-Load-Lift-Chart-Plate-/254663113941?_trkparms=aid%3D1110006%26algo%3DHOMESPLICE.SIM%26ao%3D1%26asc%3D20160323102634%26meid%3D7d37170c6b8e4c64a846c3b88bd55fe6%26pid%3D100623%26rk%3D2%26rkt%3D5%26sd%3D32441047).
- [42] FALC srl, Shredders for open field - type UNIKA. 2021. <https://www.falc.eu/en/prodotti/trincia/unika.php>.
- [43] DTE-EQUIPMENT, Hardi Zebra Mistblower. 2021. <https://www.dte-equipment.com.au/product/hardi-zebra-mistblower/>.
- [44] FALC srl, Shredder for maintenance (lateral and rear) - type T.L.F.. 2021. <https://www.falc.eu/en/prodotti/trincia/tlf.php>.
- [45] Double A, Wessex T-350-S 3.5M Sickle Bar Hedge Cutter. 2021. <https://www.doublea.co.uk/item/509/doublea/Wessex-T-350-S-35M-Sickle-Bar-Hedge-Cutter.html>.
- [46] Zunhammer Gülle-Technic, Claas Xerion - Saddle Trac 4000. 2021. <https://www.zunhammer.de/de/produkte/selbstfahrer/claas-xerion-saddle-trac-4000>.
- [47] LosHawlos, Geräteträger Fendt F 345 GT. *Wikimedia Commons*, 2005. [https://commons.wikimedia.org/wiki/File:Fendt\\_F\\_345\\_GT\\_100\\_1744.jpg](https://commons.wikimedia.org/wiki/File:Fendt_F_345_GT_100_1744.jpg).
- [48] Provincia autonoma di Bolzano - Alto Adige, Amministrazione Provincia Bolzano. 2021. <https://www.provincia.bz.it/>.