Modelling Steep-Slope Harvesting Stability through Centre of Gravity Testing

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ABSTRACT

An increase in steep-slope harvesting brings the need for a greater understanding of how machines can operate safely and efficiently on steep terrain. This study aimed to aid the simulation of machine stability through experimental determination of the centre of gravity of harvesting machines. Testing showed that centre of gravity heights are approximately 200 mm lower than initial analytical estimates, validating the need for experimental data. Recommendations are given to streamline the testing procedure.

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BACKGROUND

Since 2010, FPInnovations has been investigating methods, technology, and procedures for harvesting steep terrain safely and efficiently. In 2011, FPInnovations developed a test procedure for evaluating the stability of harvesting equipment on steep slopes (Boswell & Parker, 2011). This procedure was field-tested in 2013 using two feller-bunchers (tilting and non-tilting cabs) (Boswell & Parker, 2015). A result of this research included the development of a computer model for assessing the stability of feller-bunchers on steep slopes (Parker, 2015). Recently, FPInnovations launched the Steep Slope Initiative (SSI, 2016) and has facilitated discussions with manufacturers and industry on this topic. Manufacturers are very interested in providing solutions to allow users to safely operate on steep slopes. Deere & Company (John Deere) expressed an interest in developing appropriate testing standards for assessing physical machine characteristics (e.g., centre of gravity [CG] position) and agreed to co-operate with FPInnovations in this endeavour. FPInnovations and John Deere developed and carried out a plan to evaluate machine CG in Dubuque, Iowa, in early 2016.

STUDY OBJECTIVE

The specific objective of this study was to:

- Develop and test a methodology for determining the physical CG location for forest machines operating on steep slopes.

A standardized procedure is necessary so that all manufacturers can determine a physical CG location using a common procedure. The location of an accurate CG position is important for assessing a machine's stability and operating performance, which would allow manufacturers to optimize their machine designs for steep-slope operation, including winch assist.

The study objective was within the scope of the FPInnovations' Steep Slope Initiative, and its key objectives:

- Improved worker safety.
- Increased operating margin.
- Increased access to economic fibre.

This study aims to improve safety for loggers and machinery operators harvesting on steep slopes by improving the knowledge of machine stability in varying terrain and reducing the risk of rollover or tipping. This study can increase the operating margin of steep-slope harvesting through reduction of work-related injuries and the associated downtime and costs. In addition, improved practices and equipment for working on steep terrain can improve. As more knowledge regarding machine stability on steep terrain is accumulated, more fibre could be accessed in areas that were previously inoperable or uneconomic.

METHODOLOGY

In early 2016, FPInnovations and John Deere developed and carried out a plan to evaluate machine CG in Dubuque, Iowa. Following is a detailed description of the testing procedure and the reasoning behind it, followed by post-testing discussion and evaluation to identify any improvements or simplifications that could be made to the test method.

Previous testing on feller-buncher CG has been done using a tilt table (Boswell & Parker, 2015). The approach used in this study instead uses cranes to suspend the machine from three points and then move it through the necessary positions. The main reason for this different approach was the concern for accuracy, particularly for typical load pad scales, which are not as accurate on non-level surfaces. The position of the load pads needs to be accurately measured, so there is more room for error with the use of multiple load pads, their orientation, and location variations. The use of tension load cells at three clearly defined attachment points reduces the measurement error.

CG estimation theory

The intent of the test procedure is to determine the CG locations of the main machine components, which, in the case of a feller-buncher, are the track and house assemblies. This experimental approach is useful for the machine house and tracks because they are large, complex, dynamic bodies that are difficult to evaluate analytically. The mass distribution of the system can change during operation as the machine tilts, due to the change in position of fluids and other moving parts. The boom and head of each machine can be described analytically with accuracy, so they were removed to simplify the test procedure and analysis.

The test methodology was based on the change in the tested machine's CG location as the machine was moved through different positions in space. The loads acting on the suspended lines are influenced by their attachment location and their CG location, allowing the CG location to be estimated. Figure 1 illustrates how the horizontal distance from the cable attachment points to the CG location change to maintain balance as one end of the machine is tilted upward. On the right side of the figure, the machine is tilted to $\theta = 15°$, and both the forward distance D_0 and rear distance E_0 are decreased. Due to the geometry of the system, the front difference $\Delta D = D_{new} - D_0$ is greater than the rear difference $\Delta E = E_{new} - E_0$, resulting in increased loading on the front cable (F_{front}) and decreased loading on the rear cable (F_{rear}).

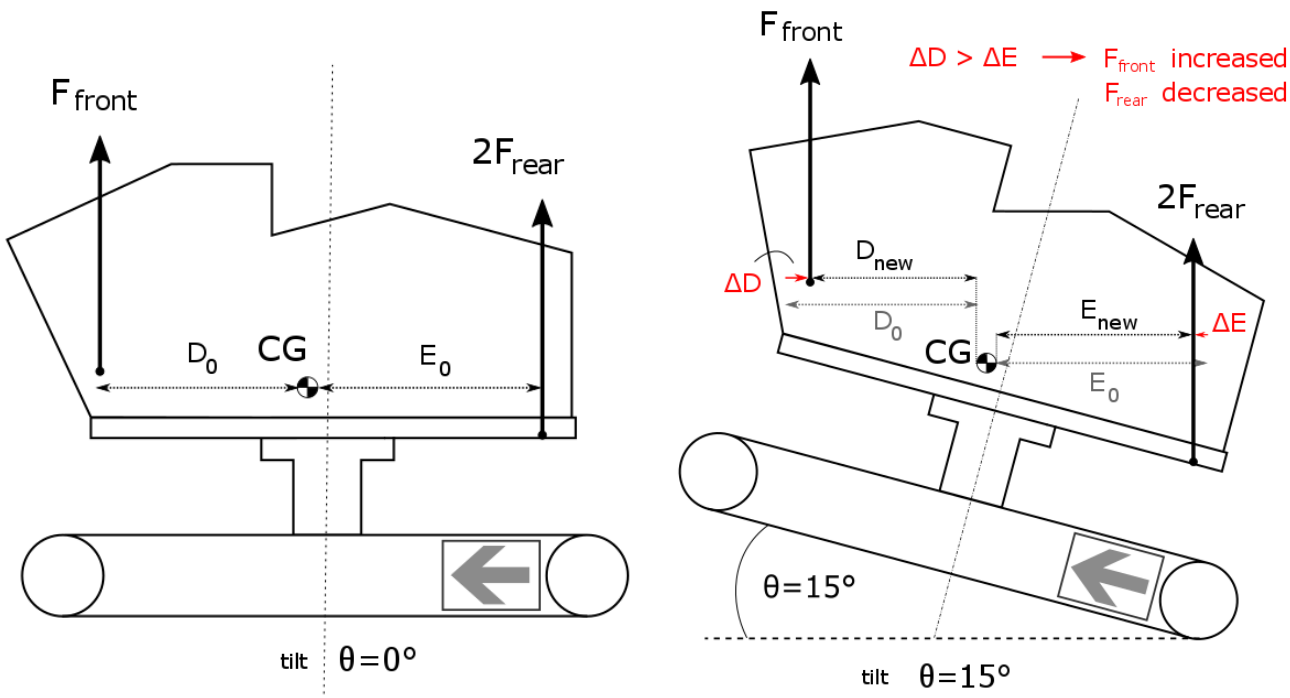
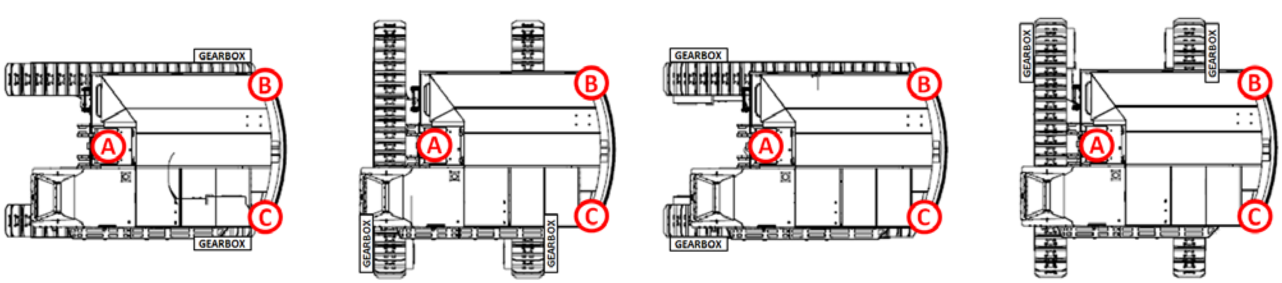


Figure 1. Centre of gravity location changes as a result of machine tilt (θ).

An additional point of interest was the change in overall CG as the tracks were rotated independently of the house. Assigning the track assembly its own CG allowed the inclusion of track rotation (and, for the 959M levelling machine, track tilting) to the test parameters. Track rotation through 90° intervals, as seen in Figure 2, allowed a satisfactory range for testing. Figure 3 shows how the track CG and, therefore, the overall CG of the machine changed as the tracks were rotated. In the example, the tracks were rotated from 0° to 180°, shifting the CG of the track assembly toward the front of the machine, due to the gearbox, and increasing the load (F_{front}) on the front cable.



0°	90°	180°	270°

Figure 2. Track rotation angles used in testing.

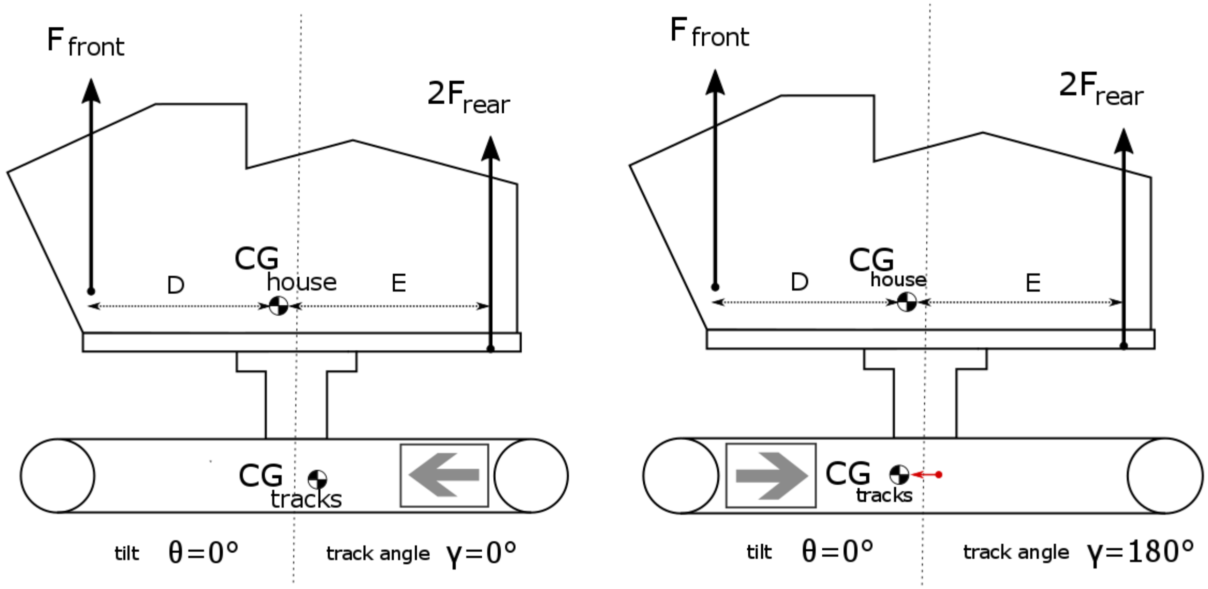


Figure 3. Centre of gravity location changes as a result of track rotation (γ).

Resources

The following resources were used for testing:

- Machinery tested booms and heads removed.
    - For this test, the John Deere 953M (non-levelling cab) and 959M (levelling cab) were used.
- Cranes (three)
    - Two cranes with a minimum load rating of 0.5 times machine weight (rear).
        - Grove TMS500E used in testing
    - One crane with a minimum load rating of 1.5 times machine weight (front).
        - Grove TMS9000E used in testing
- Communication equipment (e.g., radios) to direct and coordinate crane movement.
- Mounting hardware for crane/machine interface.
    - The front cable was attached at the boom pin location.
    - A thick (30 cm) strap was passed beneath the rear of the machine and connected to the two rear cranes. A steel bracket was welded onto the machine to prevent the strap from slipping at high inclination.
- Inline load cells (three) with ratings matching those of the corresponding cranes.
- Data acquisition system and instrumentation for monitoring load cells.

- Digital inclinometers with remote display (four).
    - Two inclinometers for house tilt (953M and 959M) – pitch and roll.
    - Two inclinometers for track tilt (959M only) – pitch and roll.

See Figure 4 for an overview of the main components of the crane mounting setup.

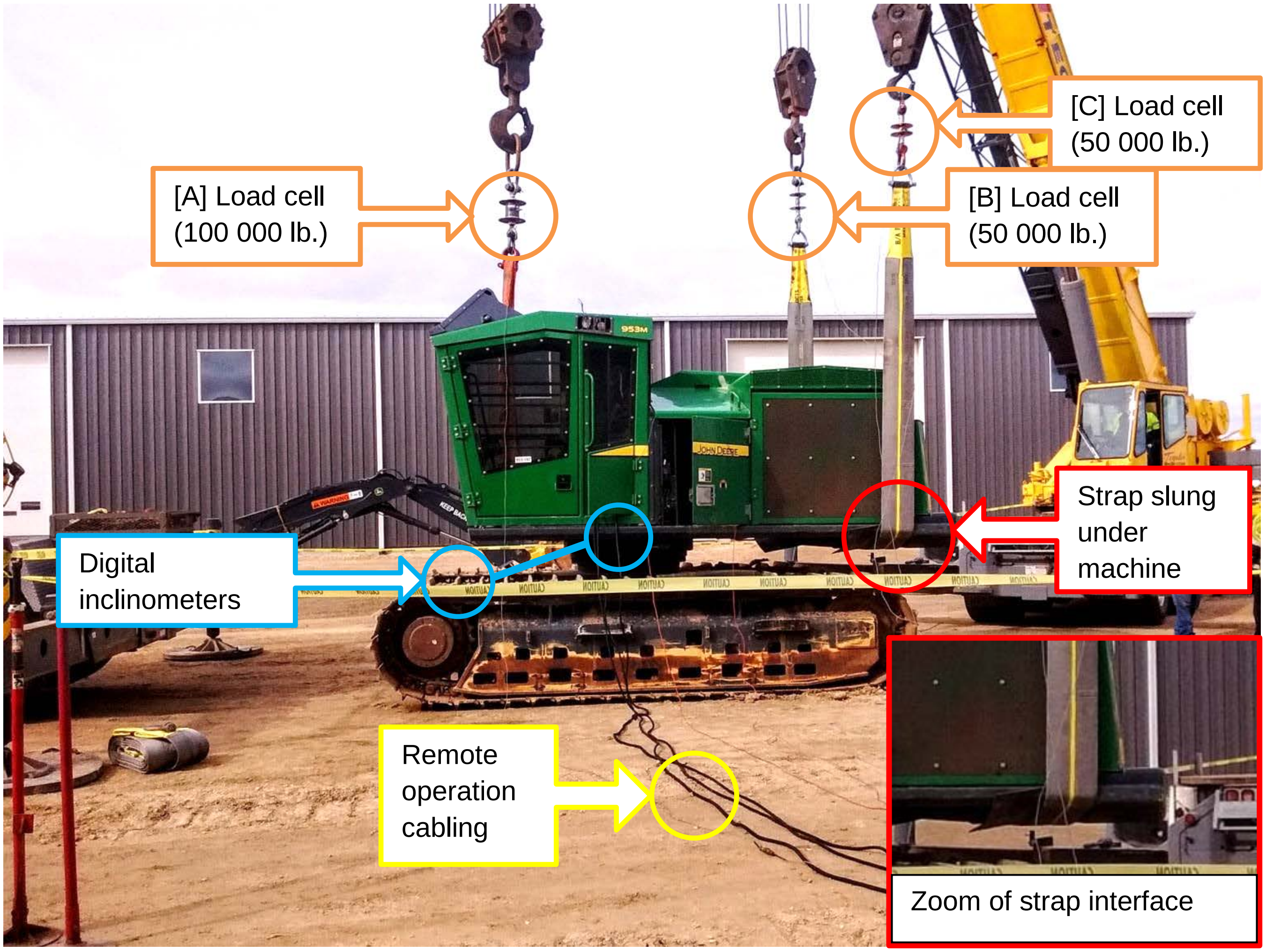


Figure 4. Crane mounting setup and equipment.

Test setup

The machines that were tested were prepared as follows:

- Booms and heads of both machines (953M and 959M) were removed.
- All fuel and fluid levels were set to the maximum allowable level.
- Machine controls were removed from the cab and set up to allow remote operation at a distance (Figure 5).

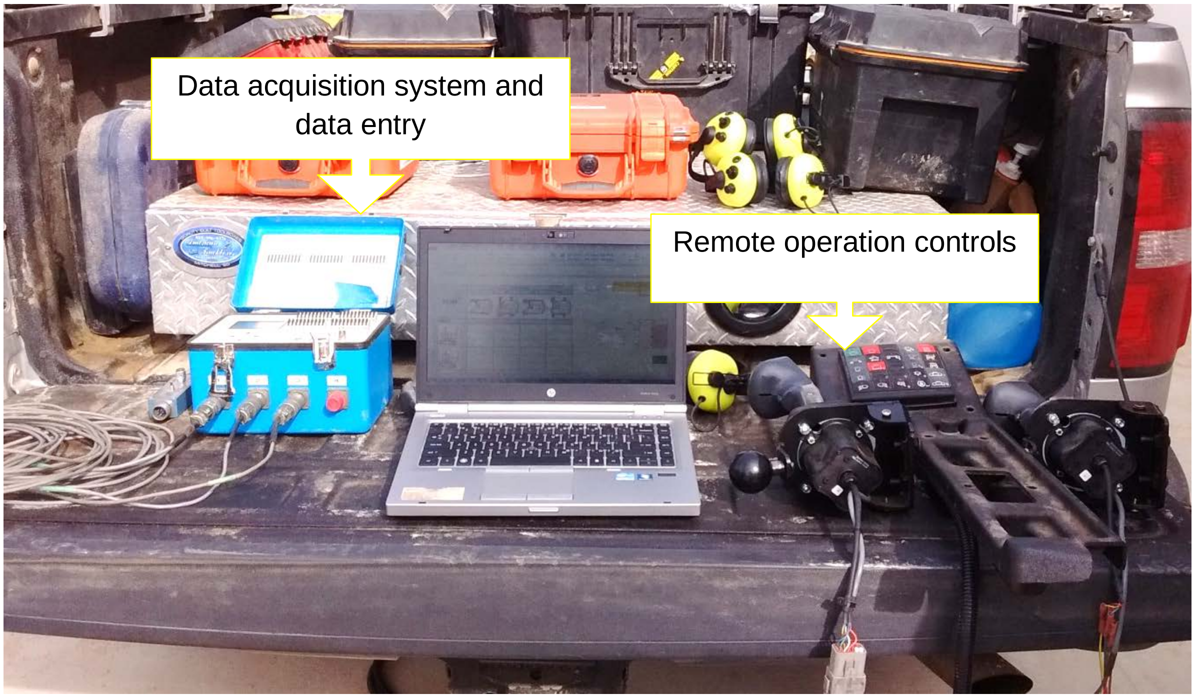


Figure 5. Data collection hardware and remote operation controls.

Three cranes were laid out to test one machine at a time:

- The largest crane (1.5 times machine weight capacity) was used to support the front of the machine.
- The two smaller cranes (0.5 times machine weight capacity) were used to support the rear of the machine. A thick strap was slung under the rear of the machine and attached via cables to the two rear cranes. To reduce the risk of the strap slipping, a supporting bracket was welded on during testing. Initially, the lift points at the top of the engine compartment were intended as lift points. However, it was estimated that in some of the intended test positions, the lift point capacity of these lift points would be exceeded, so a sling under the counterweight was used instead. This highlights the need to carefully assess whether a chosen lift point capacity is sufficient to handle the anticipated load range.

See Figure 6 for a layout of the test site.

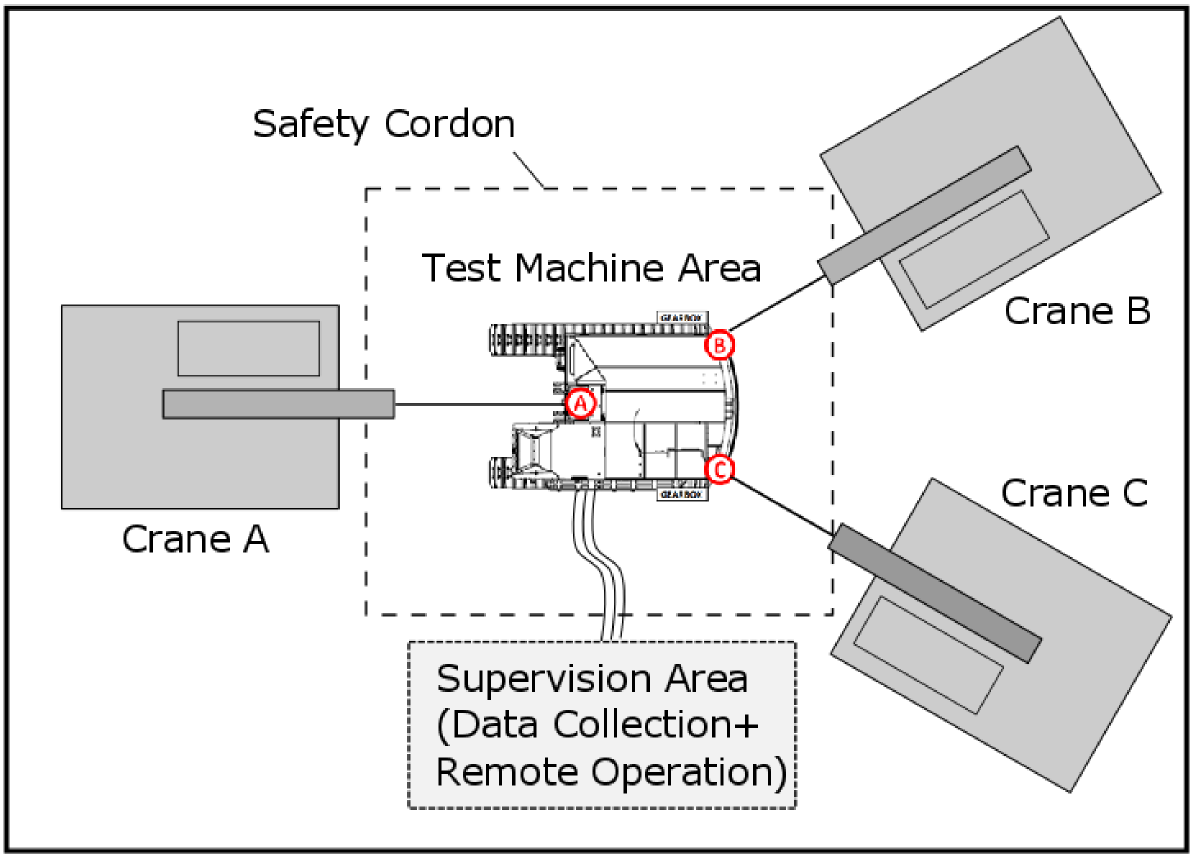


Figure 6. Test site layout.

Test procedure

The testing procedure relied on constant communication on a shared radio channel between the test directors and the crane operators. The test was directed and the resulting data monitored at a safe distance from the working machines:

- Machine control was handled remotely by the main test director.
- Machine house and track inclination were monitored through a series of remote inclinometers.
- Incoming data from the load cells on each crane's mounting point was recorded electronically and manually.

Note: Cable management was important to prevent the moving machine house and tracks from damaging cables or equipment.

The target test positions measured for each machine are summarized in Figures 7 and 8.

953M (non-levelling) testing positions

The non-levelling 953M was tilted by the cranes to five positions between +15º and -20º, as shown in Figure 6. At each position, the tracks were rotated to 0º, 90º, 180º, and 270º, resulting in a total of 20 positions.

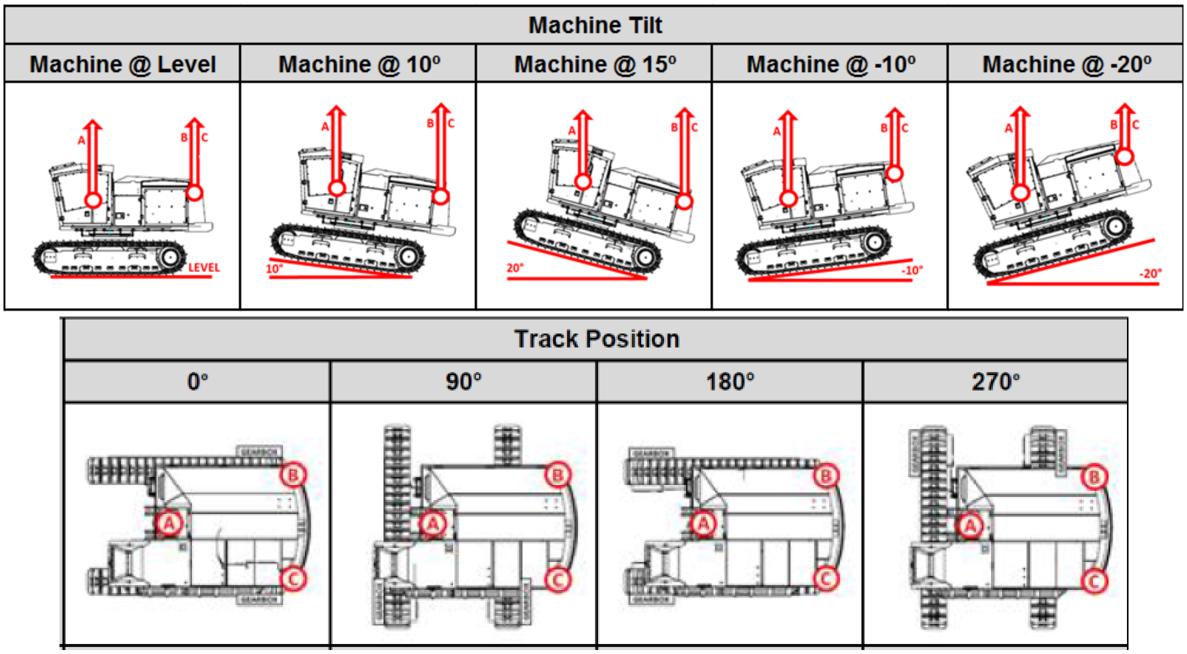


Figure 7. 953M testing positions for each variable.

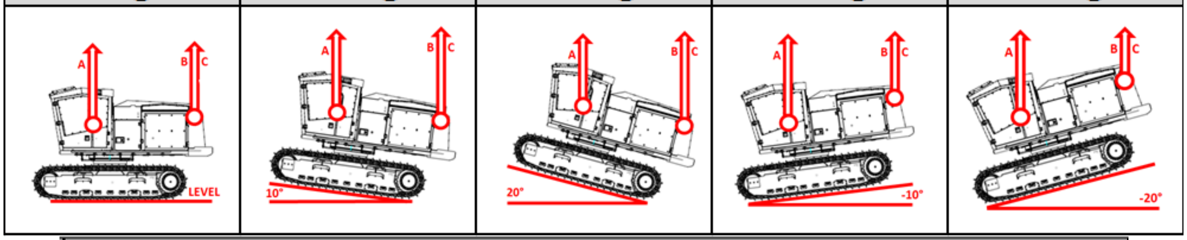
959M (levelling) testing positions

The levelling 959M was tilted to the same five positions between +15º and -20º as the 953M, and with the same track rotations.

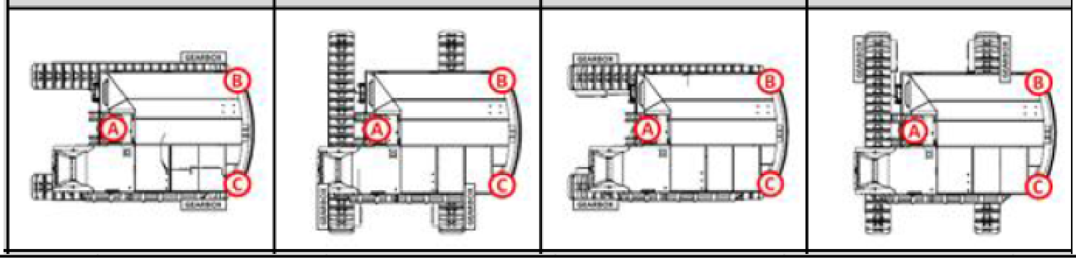
Following these, the machine house was returned to 0º and the undercarriage was taken through its range of motion to provide an additional six positions, including the maximum undercarriage tilt in each direction (independently). The tracks were not rotated for these positions, which brought the total number of positions measured for the 959M to 26.

A summary of the positions for each tested variable is shown in Figure 8.

Machine Tilt				
Machine @ Level	Machine @ 10º	Machine @ 15º	Machine @ -10º	Machine @ -20º



Track Position			
0°	90°	180°	270°



Machine Tilt & Leveling Undercarriage Tilt					
Machine @ Level	Machine @ Level	Machine @ Level	Machine @ Level	Machine @ Level	Machine @ Level
Undercarriage 10˚ FW	Undercarriage 20˚ FW	Undercarriage Full FW ~24º	Undercarriage Full BW ~5º	Undercarriage Full Left ~12º	Undercarriage Full Right ~12º

Figure 8. 959M testing positions for each variable.

Calculation of CG position

The test theory was based on the change in CG location when the machine was tilted to different positions and the tracks rotated relative to the house. See Figures 9 and 10 for a free body diagram representation of the machine. The variables h_x, h_y, h_z represent the position of the CG of the machine house, while t_x, t_y, t_z represent the position of the CG of the tracks. All positions were measured with respect to the reference point O, which was placed at the centre of the bottom of the machine house.

Note that as a simplification, and to ensure proper sign as the tracks rotated, the variables t_x, t_y were replaced by the formulaic variables a and b (track angle represented by γ, values of 0°, 90°, 180°, and 270°).

$$a = t_x \cos(\gamma) - t_y \sin(\gamma) \qquad \text{and} \qquad b = t_y \cos(\gamma) + t_x \sin(\gamma)$$

Due to the complexity of both the house and track masses, these were also considered as unknowns, represented as weights in Figures 9 and 10 by M_h and M_t. Other geometry and the measured forces $F_{A,B,C}$, tilt angle θ, and track angle γ were known.

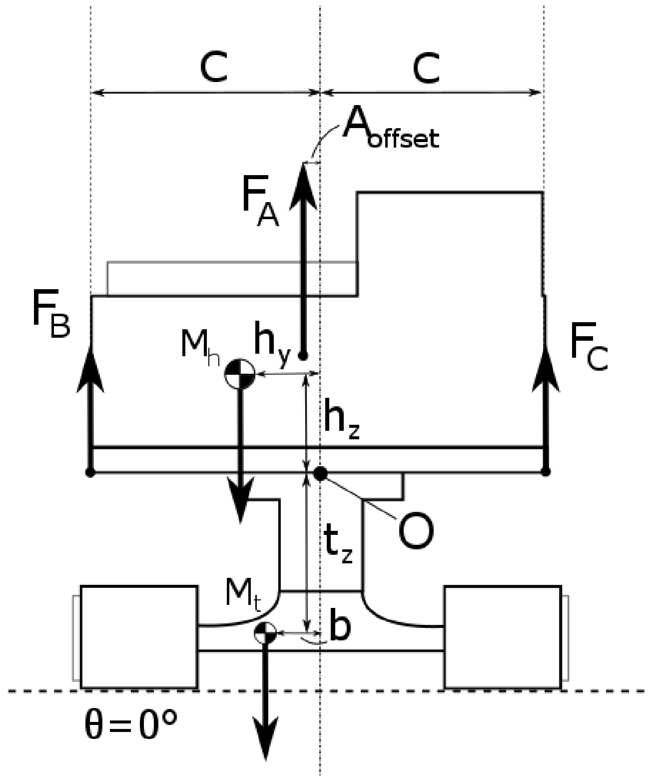


Figure 9. Two-dimensional free body diagram (y-z plane at 0º).

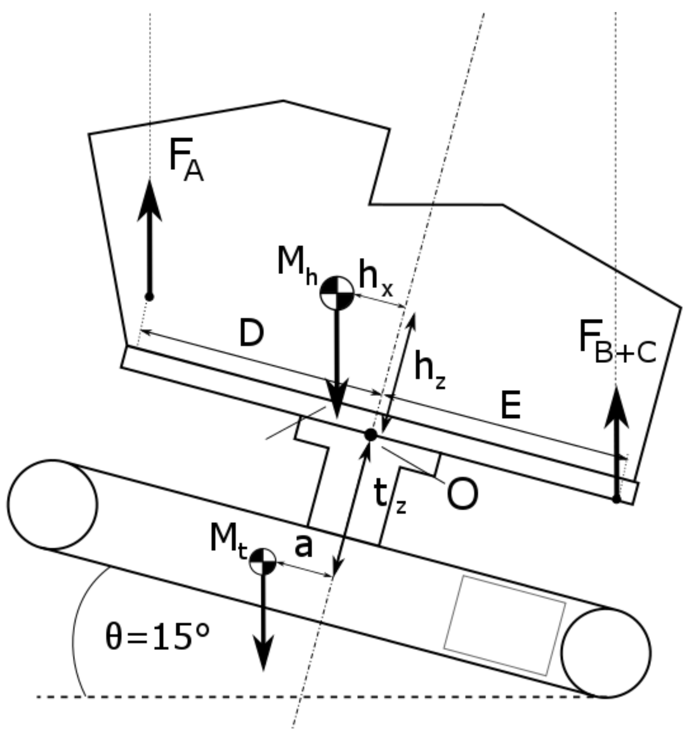


Figure 10. Two-dimensional free body diagram (x-z plane at 15º).

The system of equations is non-linear and requires the use of a non-linear solver to solve for the variables. To solve for the eight unknowns $\hbar_x, \hbar_y, \hbar_z, t_x, t_y, t_z, M_{\hbar ouse}, M_{tracks}$, the forces were equalized in the vertical direction (relation constant through testing):

$$F_A + F_B + F_C = M_{\hbar ouse} + M_{tracks}$$

The remaining equations were then taken from the sum of moments in the x-z plane and the y-z plane:

x-z plane sum of moments:

$$M_{\hbar}(\hbar_z sin\theta - \hbar_x cos\theta) - M_t(t_z sin\theta + a * cos\theta) = -F_A(Dcos\theta - A_z sin\theta) + (F_B + F_C)Ecos\theta$$

y-z plane sum of moments (simpler because only tilting in the θ direction [x-z plane] was considered).

$$M_{\hbar} * \hbar_y - M_t * b = F_A * A_{offset} + (F_B + F_C)C$$

These equations were analyzed based on the measured test angles for $\theta: 0°, 10°, 15°, 20°$ and $\gamma: 0°, 90°, 180°, 270°$ to provide the necessary system of equations for the solver.

Using a multiple equation solver (Microsoft Excel version), the CG locations for the tracks (t_x, t_y, t_z) and house ($\hbar_x, \hbar_y, \hbar_z$) were estimated and compared with analytical estimates provided by John Deere before the tests.

RESULTS AND DISCUSSION

Testing

The estimated CG positions for the two machines were calculated using the equations developed previously in conjunction with an equation solver and are summarized in Table 1. The X (fore/aft) and Y (lateral) track positions were within 10 mm of the John Deere analytical estimates for both machines, except for the non-tilting X position, which was biased forward 44 mm from the estimate. The house X positions determined in the test were 109 and 91 mm closer to the turn centre than estimated by John Deere. The house Y positions determined in the test were biased 59 and 199 mm to the left (cab side) for the two machines, whereas John Deere did not provide estimates for that location. The most noteworthy difference between the test and the John Deere estimates was for the house Z position (height), with test levels of 196 mm and 257 mm lower than estimated by John Deere.

Table 1. Comparison of measured machine centre of gravity positions (in mm) with original estimates

Component[a]	JD 953M	JD 959M
	Test vs. JD estimate	**Test vs. JD estimate**
Tracks		
X	+ 44	+ 9
Y	- 8	+ 10
Z	+ 0 [b]	+117
House		
X	+109	+ 91
Y	- 59	-199
Z	-196	-257

[a] X and Y coordinates relative to machine rotation centre; Z coordinates relative to ground
[b] Assumed to be equal to John Deere (JD) estimate

Through the data analysis process, some error was found in the balancing of equations. Possible causes of error include:

- Variation in crane cable angles.
- Location of crane mounting points.
- Precision of machine angles.

During this test, machine and track angles were monitored carefully, but the angle of the crane cables was assumed to be 0°, or purely vertical, at all times. Variation in these angles could skew the geometry of the system and introduce error. Variation could be due to wind or simply machine position.

Due to concern over the yield limit of the initially considered rear mounting points on the machines, the machine was slung between the two rear cranes using a strap under the rear end of the machine. Although the strap did not noticeably shift, the contact points could not be measured as precisely as if mounting points for hooks had been used, and the complexity and flexibility of the larger strap surface could have contributed to error.

Although the test position angles were monitored throughout the testing, some precision may have been lost if the angle varied from the predetermined values. In addition, any non-tilting parts of the machine were checked to be level at each position, but any variation could have had an effect on the final results.

It is also important to note that for the non-tilting machine (953M), it was not possible to determine the house and track Z positions independently due to the fixed Z axis connection between them. Therefore, in this case the track Z position was assumed (based on the John Deere estimate) and the house Z position was calculated.

The use of suspension by cranes instead of other methods of tilting, such as a tilt table, was an innovative solution that shows promising results.

This method has several advantages:

- Cranes are a widely available option (particularly for rental), while purpose-built tilt tables are a specialized and expensive piece of equipment.
- The suspended method is flexible with regard to location and ground surface.
- Many load cells are designed to accept only loads normal to the cell surface. When flat load cells are used on a tilted surface, the lateral loading on the load cells can affect results. This is overcome using the crane method.
- Suspension by crane allows for easy manipulation of the tracks and house levelling system without having to move the whole machine.
- The suspended method eliminates clearance issues that may arise with tilt table testing.

However, some disadvantages to this approach were discovered during testing, including:

- The suspension of the machine allows for the possibility of dynamic variations in the machine's position due to wind or due to the momentum initiated by moving through test positions. This can be mitigated by careful monitoring of the machine position, waiting for periodic motion to die down, and choosing an appropriate testing site and conditions.
- If multiple cranes and operators are used, the speed and precision of testing depend on the skill of the operators, as well as on constant monitoring and communication from the test director.
- The mounting points on the machine for the crane cables must be chosen carefully and should be rated to the appropriate load while providing a precise location of force. The strap sling used in the testing in this study was adequate, but it may have contributed to imprecision in the data.

It could be possible in future tests to suspend the rear of the machine from two fixed points on a suspended beam, thus requiring only one crane to tilt the machine. While this would limit movement to one axis, the possibility for operator error and inaccuracy would be reduced. In addition, costs from the additional cranes and operators would be eliminated.

Minimizing test positions

An important step to creating an efficient and standardized testing procedure is to minimize the positions that are recorded during the test.

To accurately determine the X and Y positions for the track and house, it is only necessary to rotate the tracks to the four rotated positions (0°, 90°, 180°, and 270°) while the machine is in its neutral level position. To obtain the Z positions, it is recommended that the machine be rotated to at least 15° in both the forward and rearward directions. To differentiate the track Z position from the house (for a tilting machine), it is recommended that the tilting track be rotated to its maximum tilt position (in the direction of maximum possible tilt) while the house is maintained at a level position. Therefore, only six (non-tilting) or seven (tilting) test positions are necessary to determine CG locations.

Analytical boom and head mass additions and future modelling

It is important to keep in mind the masses of the boom, stick, and head, and their impact on the stability of the machine. As previously stated, these masses were removed for the experimental CG testing because they could be modelled analytically with reasonable accuracy.

Additionally, they would introduce extra complexity into the test procedure, as the possible number of use-case positions increase dramatically. Once the results of this experimental testing are introduced into a simulation model, these additional masses can be added to match typical machines in use and to facilitate simulation with a variety of boom and head configurations.

CONCLUSIONS

- Testing was successfully completed using suspension by cranes rather than a tilt table.
- Some procedural issues were identified, including location measurement of attachment points and angular cable motion.
- Testing showed that CG heights are 196 mm lower (953M) and 257 mm lower (959M) than initial analytical estimates for the candidate machines.
- It is only possible to differentiate track and house Z positions for tilting machines. Assumptions must be made for non-tilters.
- The number of test positions can be reduced to six (non-tilting machine) or seven (tilting machine).
- Models should be updated based on new information obtained from tests.

NEXT STEPS

- FPInnovations will update a previous simulation model using the results from this testing and analytical CG data for the boom and head of the machine.
- The simulation model will be adapted to include additional factors, including soil properties and force effects from a winch-assist system.
- The test procedure will be revised and streamlined. Key points include fewer testing positions and a focus on careful monitoring of machine position for increased precision.
- Possible ways of simplifying the suspension method will be investigated (for example, three-point suspension using a single crane and two fixed attachment points).

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