



The Effect of Machine Position on Stability when Operating on Steep Slopes

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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 investigate the sensitivity of different operating positions for non-tilting and tilting machines, and to propose a methodology for determining safe operating parameters.

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BACKGROUND

Since 2010, FPInnovations has been investigating methods, technologies, 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), and a computer model was developed for assessing the stability of feller-bunchers on steep slopes (Parker, 2015). In 2015, the Steep Slope Initiative (FPInnovations, 2016) was launched by FPInnovations, which has increased cooperation between equipment manufacturers and industry on this topic. In 2016, Deere & Company (John Deere) worked with FPInnovations to develop a testing standard for assessing physical machine characteristics (e.g., centre of gravity position) and conducted testing with two feller-bunchers in Dubuque, Iowa, in early 2016 (Petch & Parker, 2017).

The cooperative testing provided accurate physical machine characteristic data for both a non-tilting (John Deere 953M) and a tilting (John Deere 959M) feller-buncher. These data were integrated into the FPInnovations computer stability model to improve modelling predictions of the relative performance of the tilting and non-tilting machines. In addition, the model was modified to investigate the following attributes:

- Movement on slope based on available traction.
- Effect of traction line (winch) forces on stability and traction.

Accordingly, FPInnovations initiated a comparative evaluation of the two feller-buncher types.

STUDY OBJECTIVES

The objectives of the evaluation were as follows:

- Determine the expected operability range of both a non-tilting and tilting feller-buncher for a range of conditions based on stability.
- Evaluate the influence of traction line orientation on machine stability.

METHODOLOGY

Assessment of machine operability limits

Simulations were conducted with the revised stability model for the following four modes of operation:

- Non-tilting machine – uphill direction.
- Tilting machine – uphill direction.
- Non-tilting machine – downhill direction.
- Tilting machine – downhill direction.

Each operating mode was evaluated at the following slopes: 30%, 40%, 50%, 60%, and 70%.

For each slope and operating mode, the following machine orientations (Figure 1) were evaluated:

- 0 degrees relative to slope direction (i.e., machine facing directly up or down maximum slope).
- 20 degrees relative to slope.
- 40 degrees relative to slope.

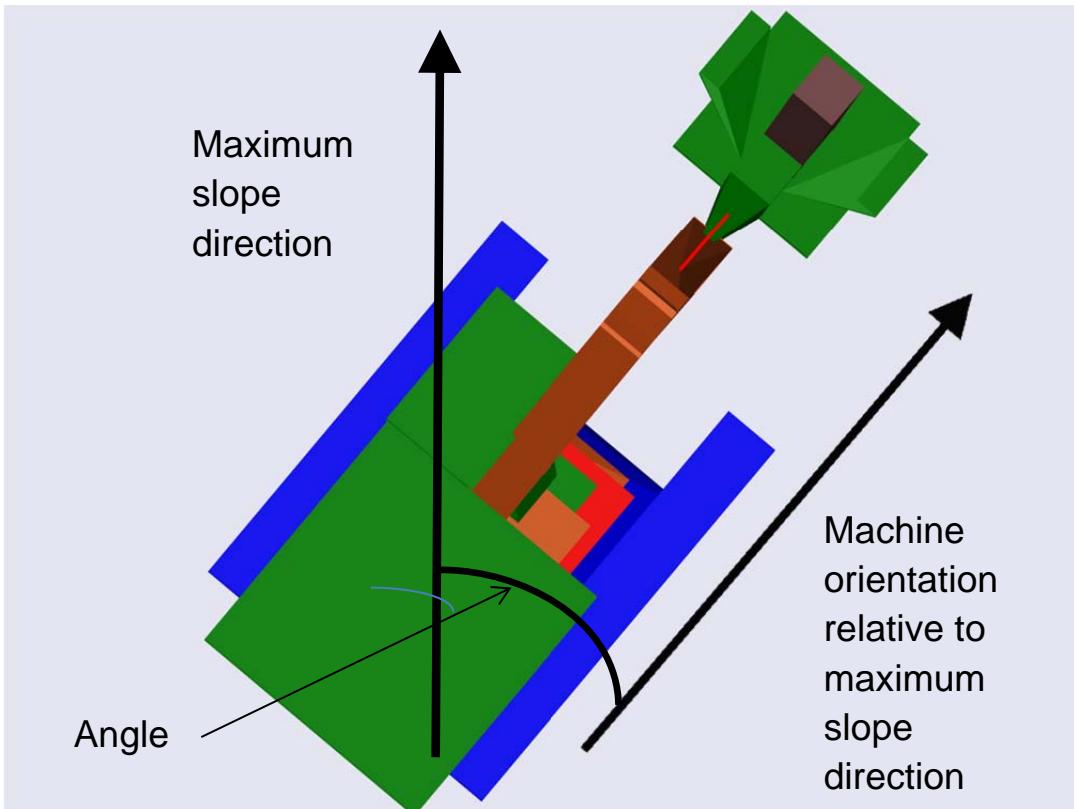


Figure 1. Machine orientation to slope (plan view).

At each slope, operating mode, and slope orientation, the following traction line loads were evaluated:

- No load.
- 10% of machine weight (40 kN).
- 20% of machine weight (80 kN).

In this evaluation, the traction line force was applied in the direction of machine travel when operating uphill and 180 degrees to machine travel when operating downhill. In both operating modes, the traction line was assumed to be parallel to the slope in the direction of travel.

For the purpose of this report, a traction force of 20% of machine weight was considered the maximum tension under “traction assist” conditions. At tension levels above this threshold, the cable provides significant support and stability to the machine.

Both the lateral (side) and longitudinal (fore-aft) stability were evaluated for each of the conditions described above for a felling head loaded with a 3-tonne payload placed at 4.8 m from the centre of the machine under the following two scenarios:

- Felling head directly in front of machine (no house rotation) (Figure 2).
- Felling head rotated 45 degrees downhill relative to machine direction (Figure 3).

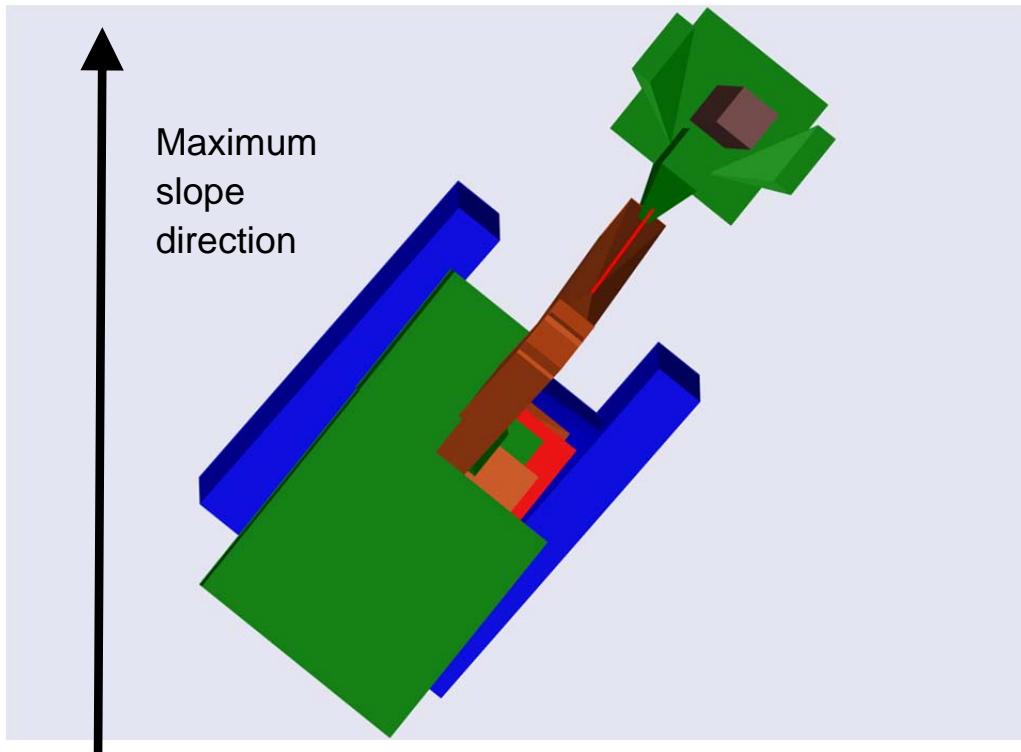


Figure 2. Felling head directly in front of machine.

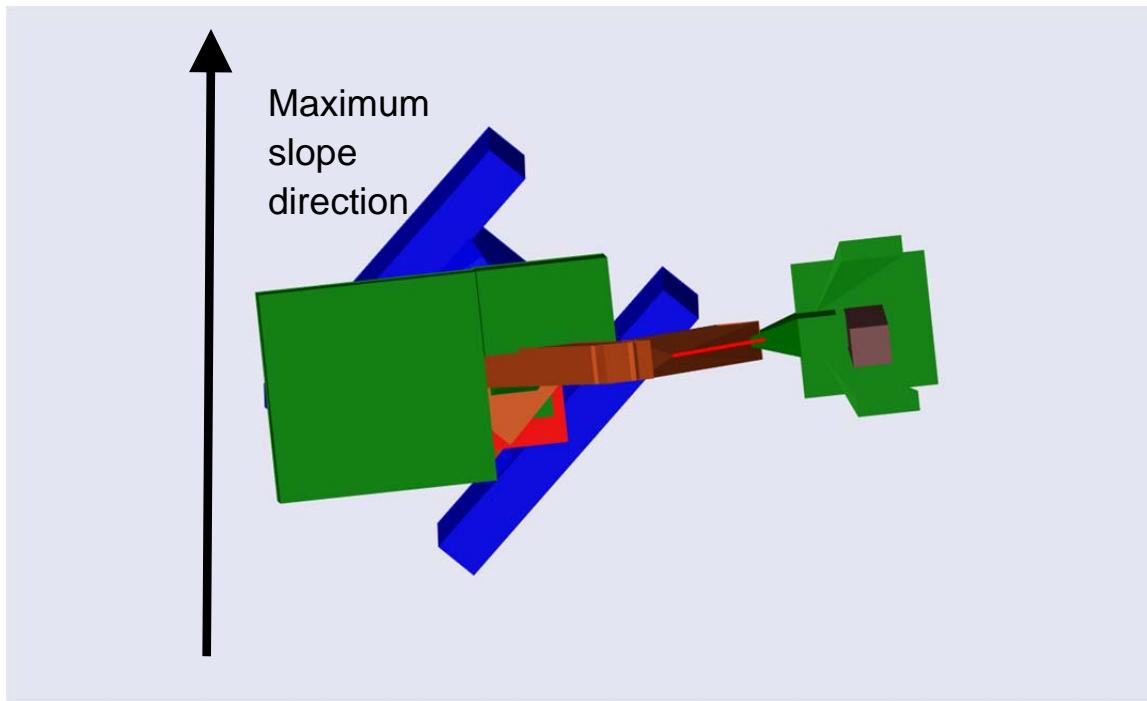


Figure 3. Felling head rotated 45 degrees downhill.

The stability is evaluated using the load transfer ratio (LTR) performance measure (Parker 2015):

$$LTR \text{ lateral} = \frac{\text{Load}_{\text{right track}} - \text{Load}_{\text{left track}}}{\text{Total Load}}$$

$$LTR \text{ longitudinal} = \frac{\text{Load}_{\text{rear}} - \text{Load}_{\text{front}}}{\text{Total Load}}$$

All evaluations were conducted at a traction coefficient of 0.5 representing a moderate level of traction.

The worst-case stability level (highest LTR) was determined from the two position scenarios (Figures 2 and 3). If the LTR was less than 0.6,¹ the machine was deemed to be capable of operating under the prescribed conditions.

Evaluation of traction line angle sensitivity

The angle at which the traction line force is applied to the machine can have a considerable impact on the stability of the machine. The sensitivity of this factor was evaluated for one case:

- Non-tilting feller-buncher.
- Uphill direction.
- Oriented at 40 degrees to the slope.
- 60% slope.
- 20% traction line tension.

Both the lateral and longitudinal stability were evaluated through simulation of traction line angles ranging from -60 to 60 degrees relative to the machine direction (Figure 4) for the two feller-buncher positions without a traction line evaluated previously:

- Felling head directly in front of machine (no house rotation) (Figure 2).
- Felling head rotated 45 degrees downhill relative to machine direction (Figure 3).

¹ A maximum LTR of 0.60 was proposed in a previous FPInnovations study (Boswell & Parker, 2015).

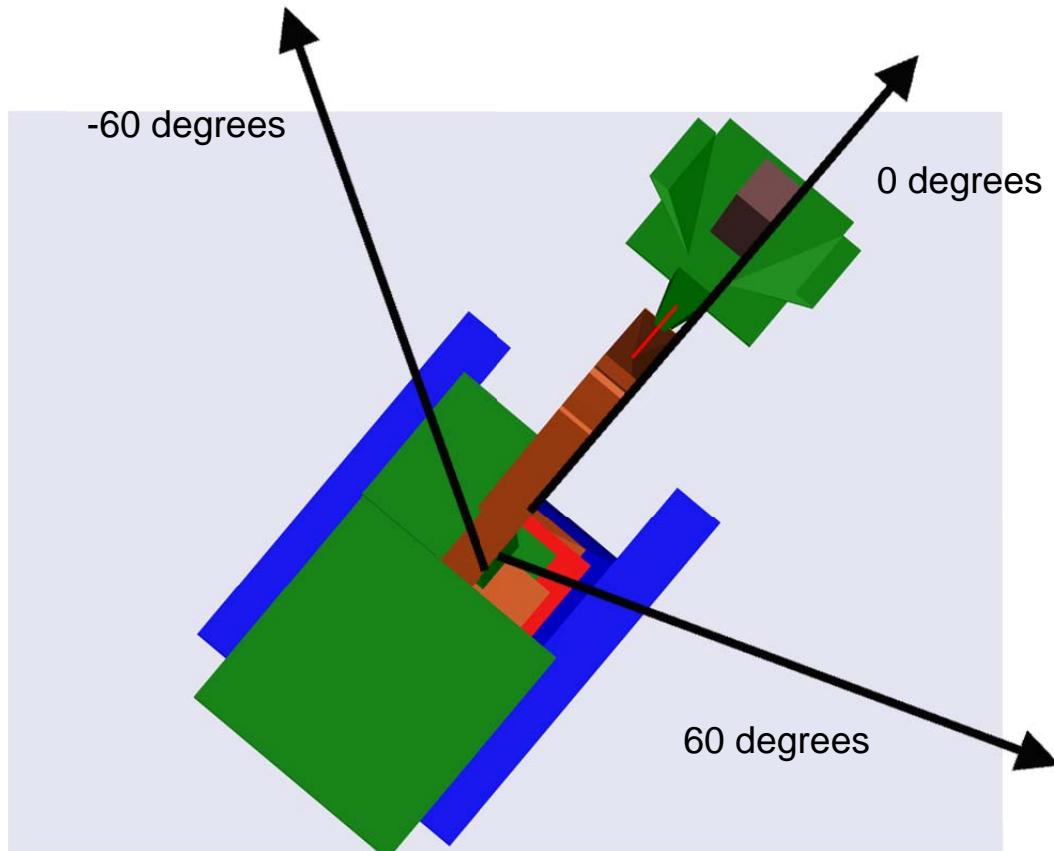


Figure 4. Range of traction line angles evaluated.

RESULTS AND DISCUSSION

Assessment of machine operability limits

Uphill operation

The estimated operability limits² for the uphill orientation are tabulated in Table 1 and Table 2 for the non-tilting and tilting machines, respectively. The operability limits are relatively good for both machines in the uphill direction with the capability of operating on 70% slopes with traction line tension of 20%. It is likely that both machines could operate on a 70% slope at the zero-degree machine orientation without any traction line tension if the available surface traction were higher. In this case, the traction coefficient was limited to 0.5. As the machine orientation to the slope increases, its range of operation decreases—particularly for the non-tilting machine as the lateral stability decreases. In the straight uphill orientation (0 degrees), both machines have the same range of operation.

² Operability limits based on simulations of machine stability. For details of specific simulation results, refer to Appendix I (LTR not exceeding +/- 0.6 for either of the two worst-case conditions evaluated).

Table 1. Stability-based operability limits: non-tilting machine; uphill orientation

Machine orientation to slope (degrees)	0			20			40		
Traction line tension (% of machine weight)	0	10	20	0	10	20	0	10	20
Slope (%)									
30	Y	Y	Y	Y	Y	Y	Y	Y	Y
40	Y	Y	Y	Y	Y	Y	Y	Y	Y
50	Y	Y	Y	Y	Y	Y	N	N	Y
60	N	Y	Y	N	Y	Y	N	N	N
70	N	N	Y	N	N	N	N	N	N

Table 2. Stability-based operability limits: tilting machine; uphill orientation

Machine orientation to slope (degrees)	0			20			40		
Traction line tension (% of machine weight)	0	10	20	0	10	20	0	10	20
Slope (%)									
30	Y	Y	Y	Y	Y	Y	Y	Y	Y
40	Y	Y	Y	Y	Y	Y	Y	Y	Y
50	Y	Y	Y	Y	Y	Y	Y	Y	Y
60	N	Y	Y	N	Y	Y	N	N	N
70	N	N	Y	N	Y	Y	N	N	N

A closer examination of the stability results at a 70% slope in the uphill direction at 20 degrees to the slope illustrates that the critical load position is when the felling head is rotated 45 degrees downhill from the machine's direction of travel (Figure 5). In this position, the non-tilting machine's lateral stability exceeds the LTR requirement of 0.60 at line tensions of 10 and 20%, whereas the tilting machine's lateral stability is below the required threshold. If the load position is limited to be directly in front of the machine as shown in Figure 6, the lateral stability of both machines is much improved. In this position, the tilting machine's longitudinal stability becomes the critical factor and is poorer than both longitudinal and lateral stability of the non-tilting machine, but still below the required LTR threshold of 0.60. When the machine orientation is increased to 40 degrees relative to the slope, the stability degrades to a point where the lateral LTR is well above the required 0.60 maximum threshold (Figure 7).

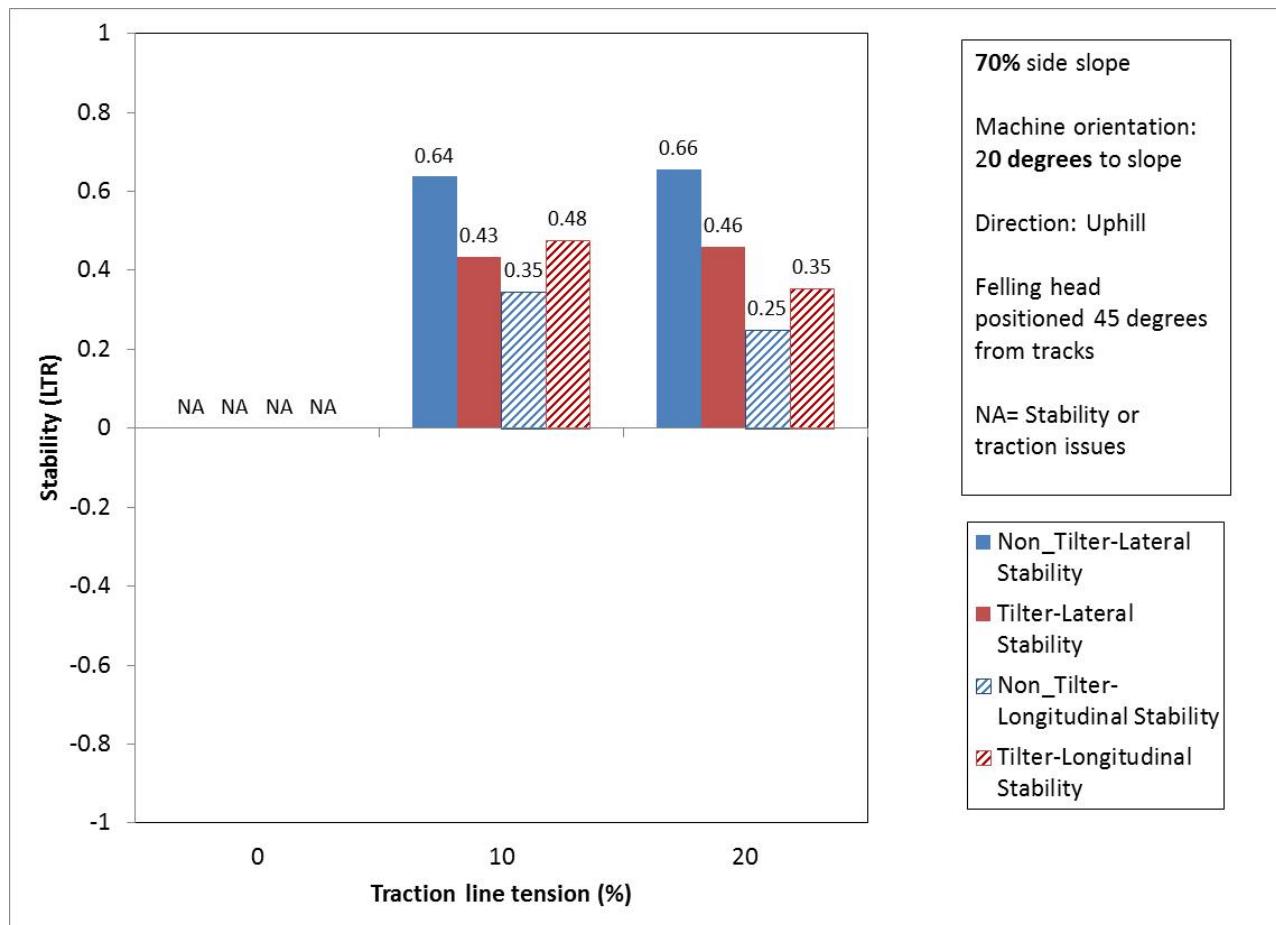


Figure 5. Stability results: uphill 70% slope, machine 20 degrees to slope, load 45 degrees rotated downhill.

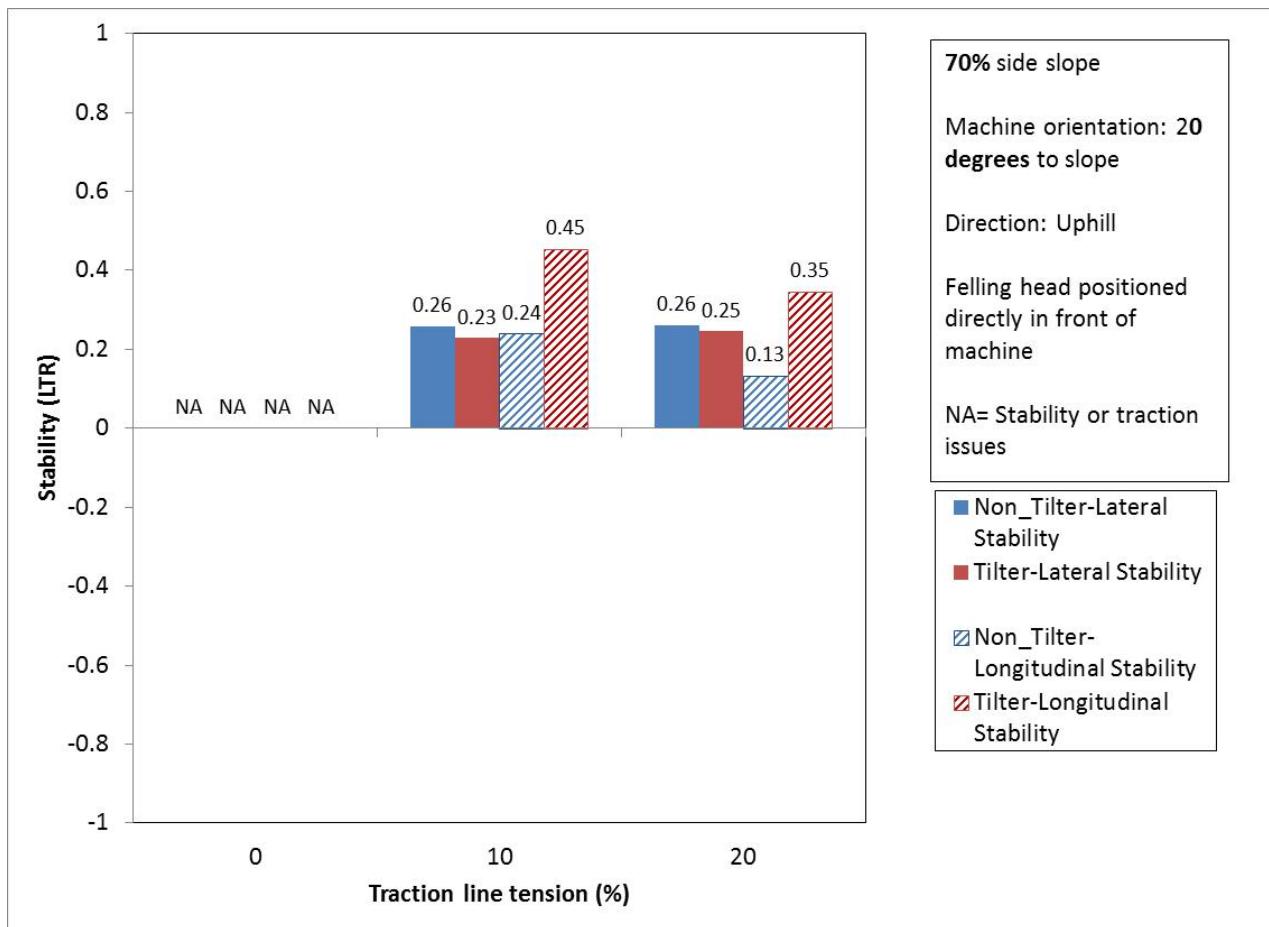


Figure 6. Stability results: uphill 70% slope, machine 20 degrees to slope, load directly in front of machine.

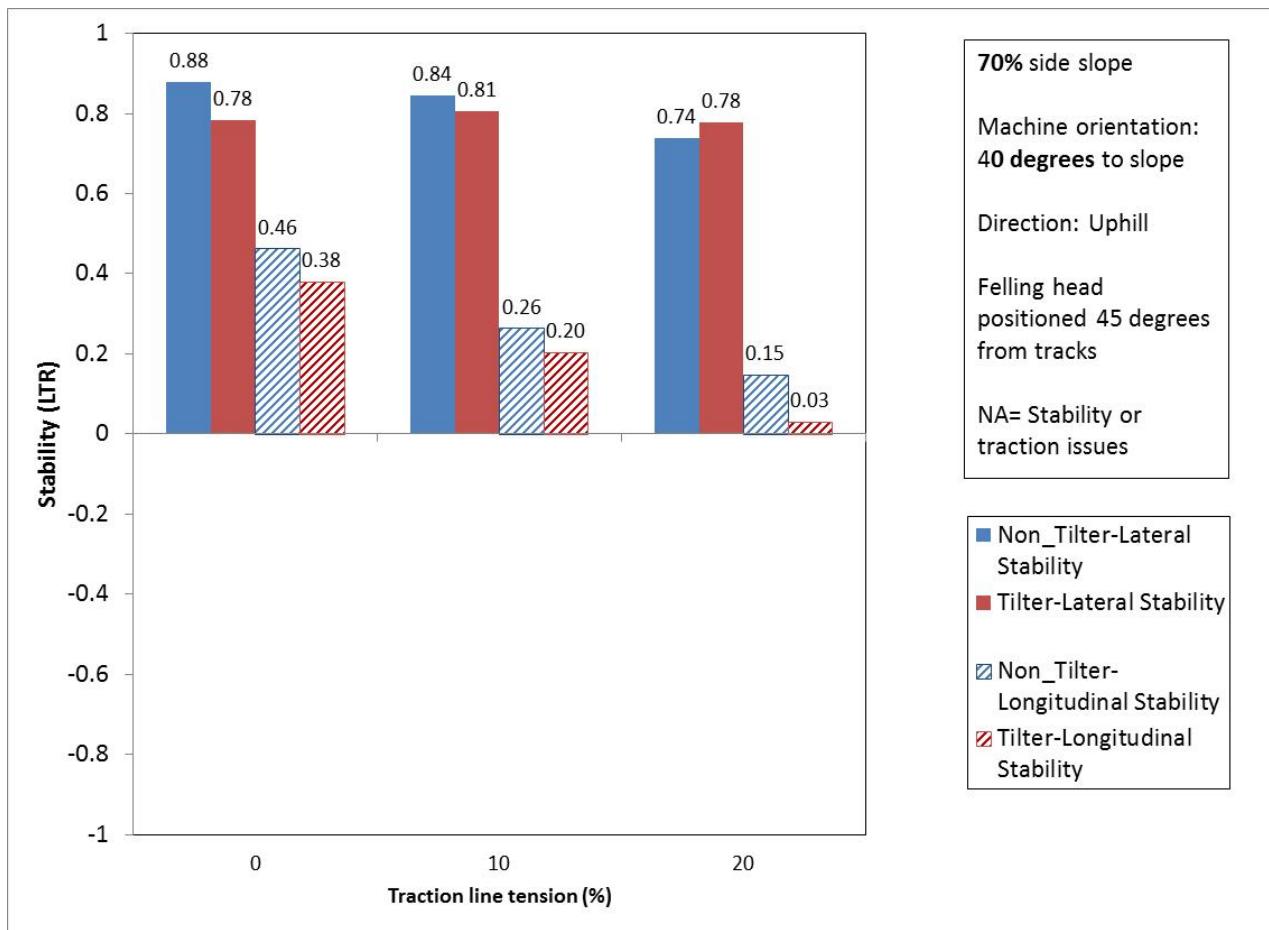


Figure 7. Stability results: uphill 70% slope, machine 40 degrees to slope, load 45 degrees rotated downhill.

Downhill operation

The estimated operability limits³ for the downhill orientation are presented in Table 3 and Table 4 for the non-tilting and tilting machines, respectively. The range of operation is much reduced for both machines when operating in the downhill direction. There are no conditions at slopes greater than 30% where either machine can operate without a traction line. The range of operation is increased slightly for the tilting machine which can operate at a slope of 40% at a traction line tension of 10%, and at a slope of 50% with a traction line tension of 20%, when orientated 0 degrees to the slope. Under the same conditions, the non-tilting machine is limited to a 40% slope with 20% line tension. It is likely that the range of operation could be increased if line tensions higher than 20% of machine weight were used. However, at this point, the harvesting system goes beyond a traction assist as defined in this report and larger-capacity traction lines or additional safety systems may be required. Tables 3 and 4 show that traction line systems should not be used in downhill orientations on slopes greater than about 40% if the maximum line tension is limited to 20% or less of the machine weight. Therefore, further analysis should be conducted to determine the required line tensions for operating downhill within the prescribed stability performance measures on slopes up to 70%.

³ Operability limits based on simulations. Refer to Appendix I for details of simulation results.

Table 3. Stability-based operability limits: non-tilting machine; downhill orientation

Machine orientation to slope (degrees)	0			20			40		
Traction line tension (% of machine weight)	0	10	20	0	10	20	0	10	20
Slope (%)									
30	N	N	Y	N	N	Y	N	Y	Y
40	N	N	Y	N	N	Y	N	N	Y
50	N	N	N	N	N	N	N	N	Y
60	N	N	N	N	N	N	N	N	N
70	N	N	N	N	N	N	N	N	N

Table 4. Stability-based operability limits: tilting machine; downhill orientation

Machine orientation to slope (degrees)	0			20			40		
Traction line tension (% of machine weight)	0	10	20	0	10	20	0	10	20
Slope (%)									
30	N	Y	Y	N	Y	Y	N	Y	Y
40	N	Y	Y	N	Y	Y	N	Y	Y
50	N	N	Y	N	N	Y	N	N	N
60	N	N	N	N	N	N	N	N	N
70	N	N	N	N	N	N	N	N	N

Generally, there are more conditions where the tilting machine can operate compared to the non-tilting machine in the downhill orientation. However, there was one case at a 40-degree orientation to the slope with 20% line tension where the non-tilting machine could operate and the tilting machine could not. In this situation, the tilting machine's lateral LTR slightly exceeds the 0.60 threshold whereas the non-tilting machine's lateral LTR is just slightly below the threshold (Figure 8). At a machine orientation of 40 degrees to a slope of 50%, the tilting machine has insufficient side-tilting capacity to completely level the machine and, therefore, cannot compensate for its higher centre of gravity position compared to the non-tilting machine. When the machine is oriented at 0 degrees to the slope in the downhill direction, the longitudinal stability typically limits the machine's operability (Figure 9).

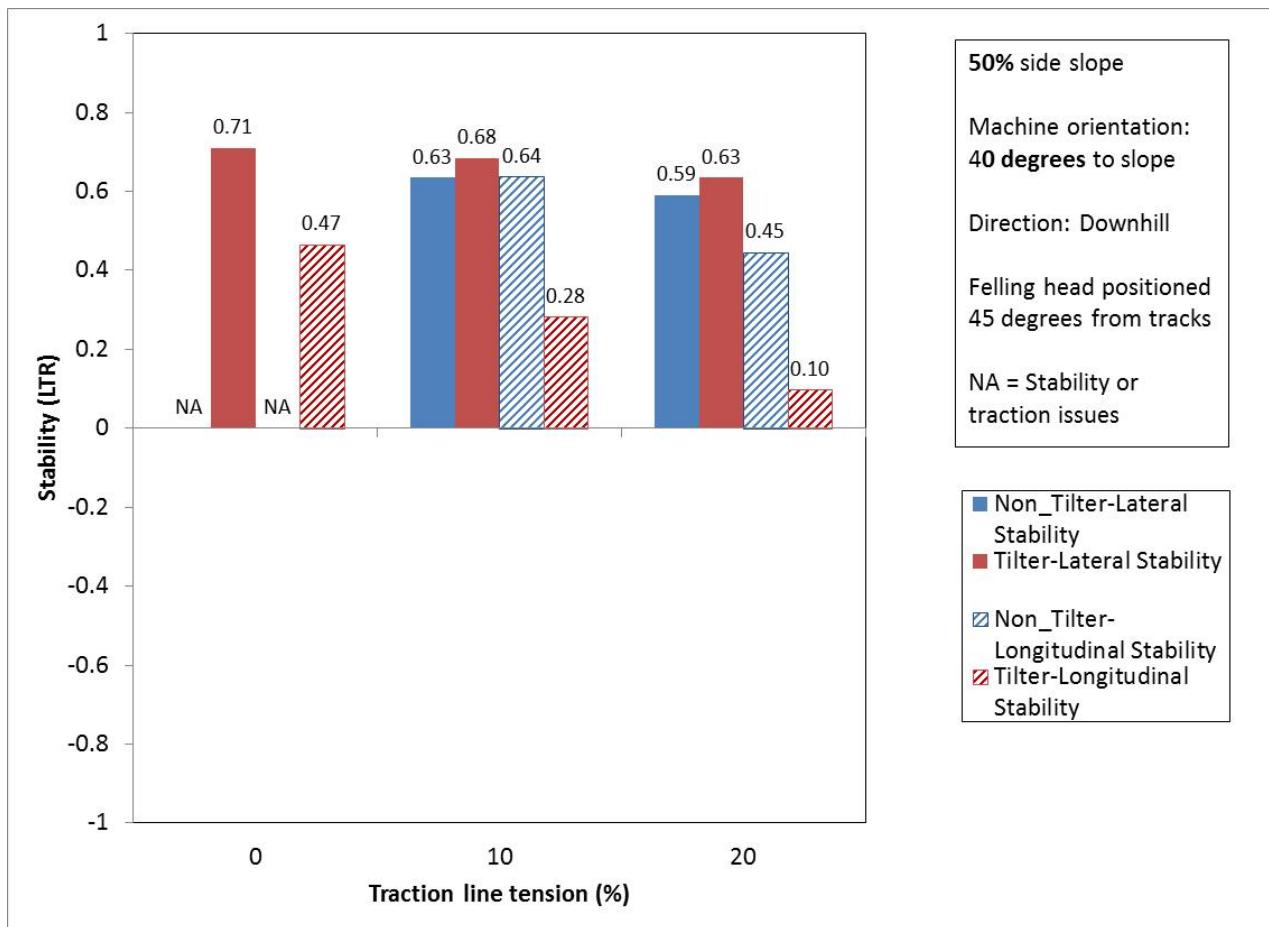


Figure 8. Stability results: downhill 50% slope, machine 40 degrees to slope, load 45 degrees rotated downhill.

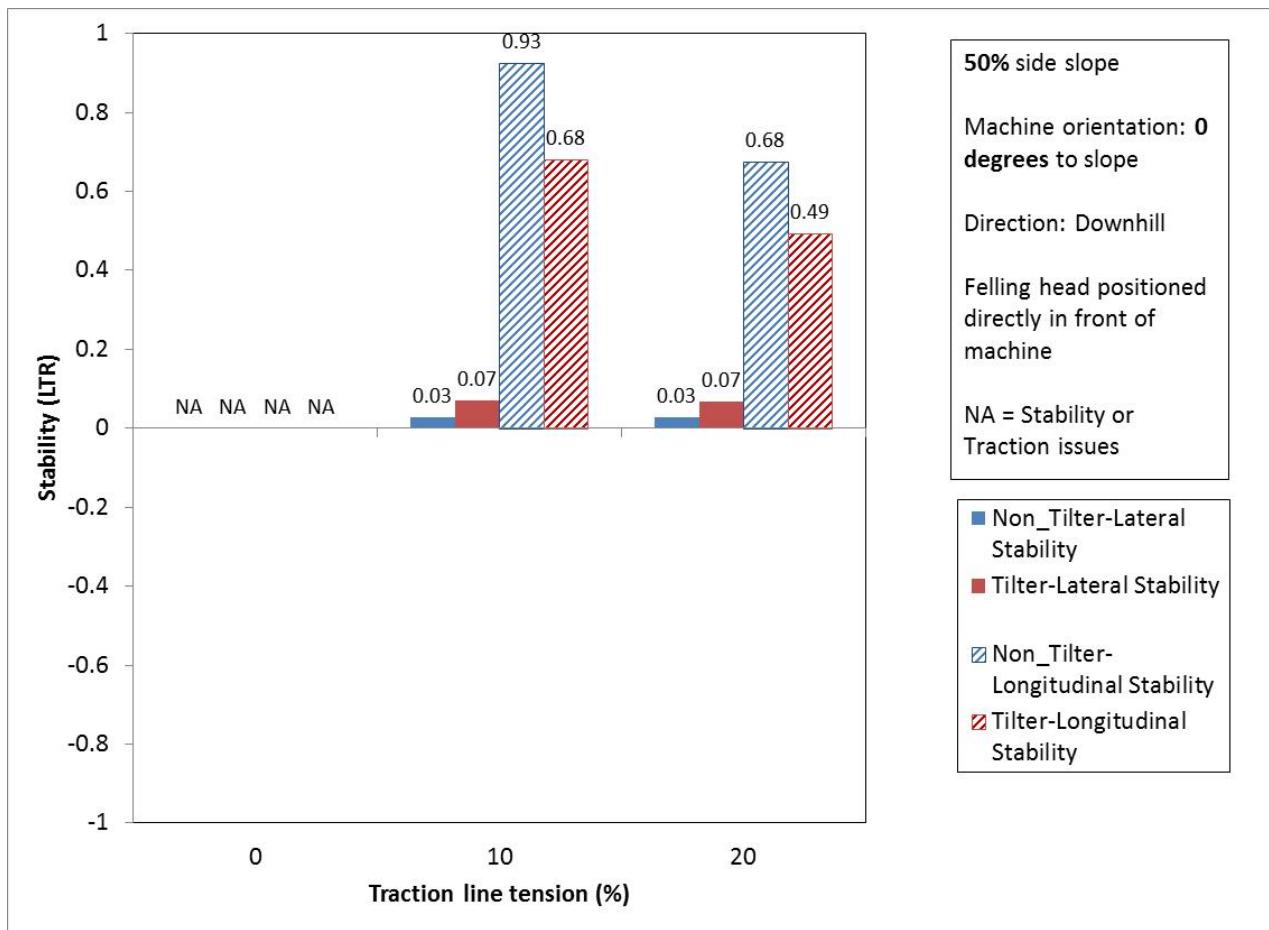


Figure 9. Stability results: downhill 50% slope, machine 0 degrees to slope, load directly in front of machine.

Evaluation of traction line angle sensitivity

The sensitivity of traction line angle on machine stability is illustrated in Figure 10 and Figure 11 for the non-tilting machine in two load positions: load directly in front of machine, and load rotated 45 degrees downhill. As noted previously, the worst-case condition occurs when the load is rotated 45 degrees downhill (Figure 11). The trends are the same for both load conditions with lateral stability optimized at maximum negative (i.e., more uphill) traction line angles while longitudinal stability was best at maximum positive traction line angles. In this case, the lateral stability is the critical factor with higher levels of LTR so the best overall stability is obtained when the traction line is positioned 60 degrees uphill from the machine's direction of travel. Based on this preliminary evaluation, a best practice is to position the traction line at as great an angle in the uphill direction as practical relative to the machine's position on the slope. At a minimum, it is recommended that traction lines should be positioned directly upslope. However, further analysis is recommended to investigate a wider range of potential operating conditions including the downhill direction.

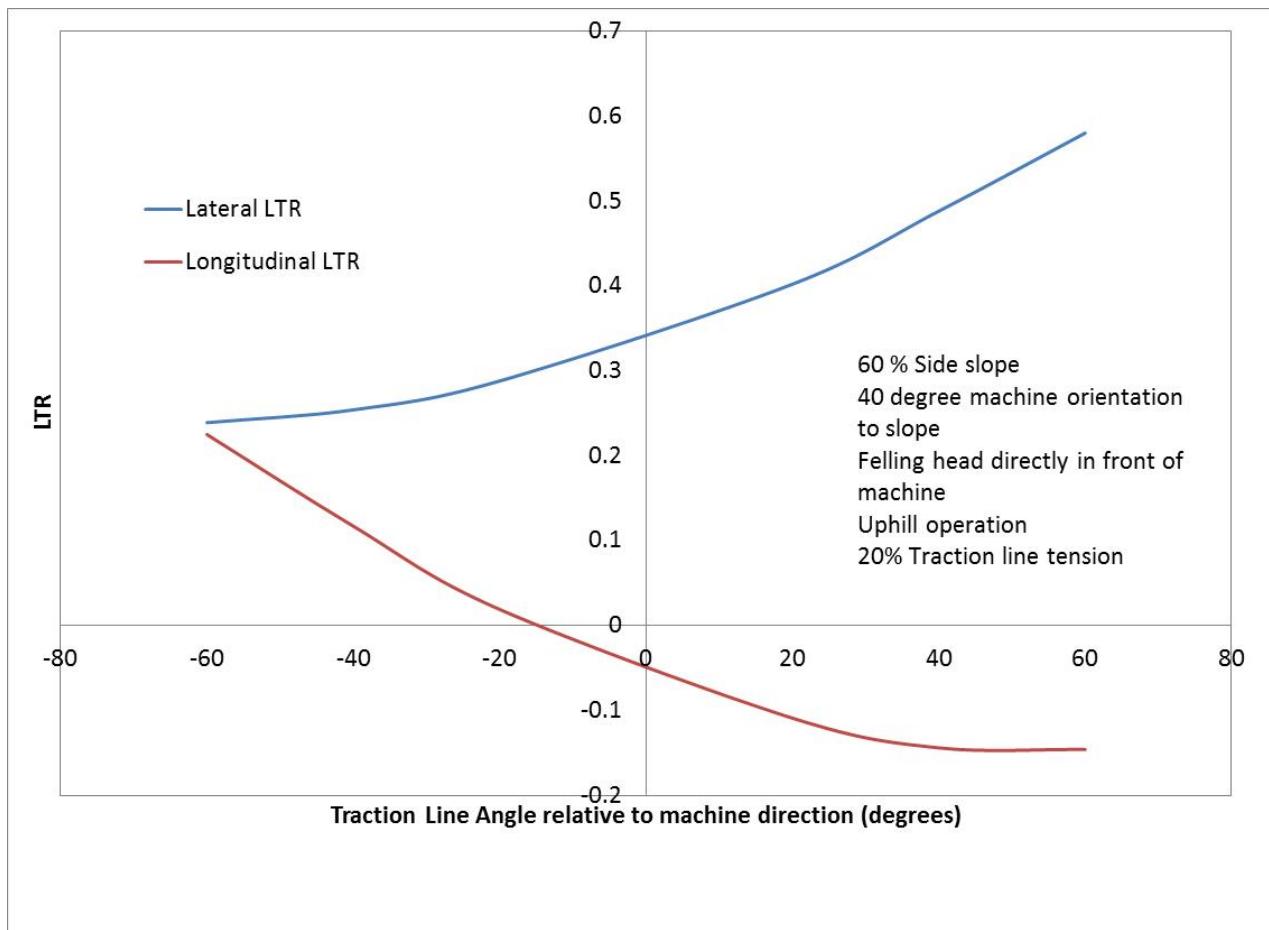


Figure 10. Traction line angle sensitivity: non-tilting machine, load directly in front of machine.

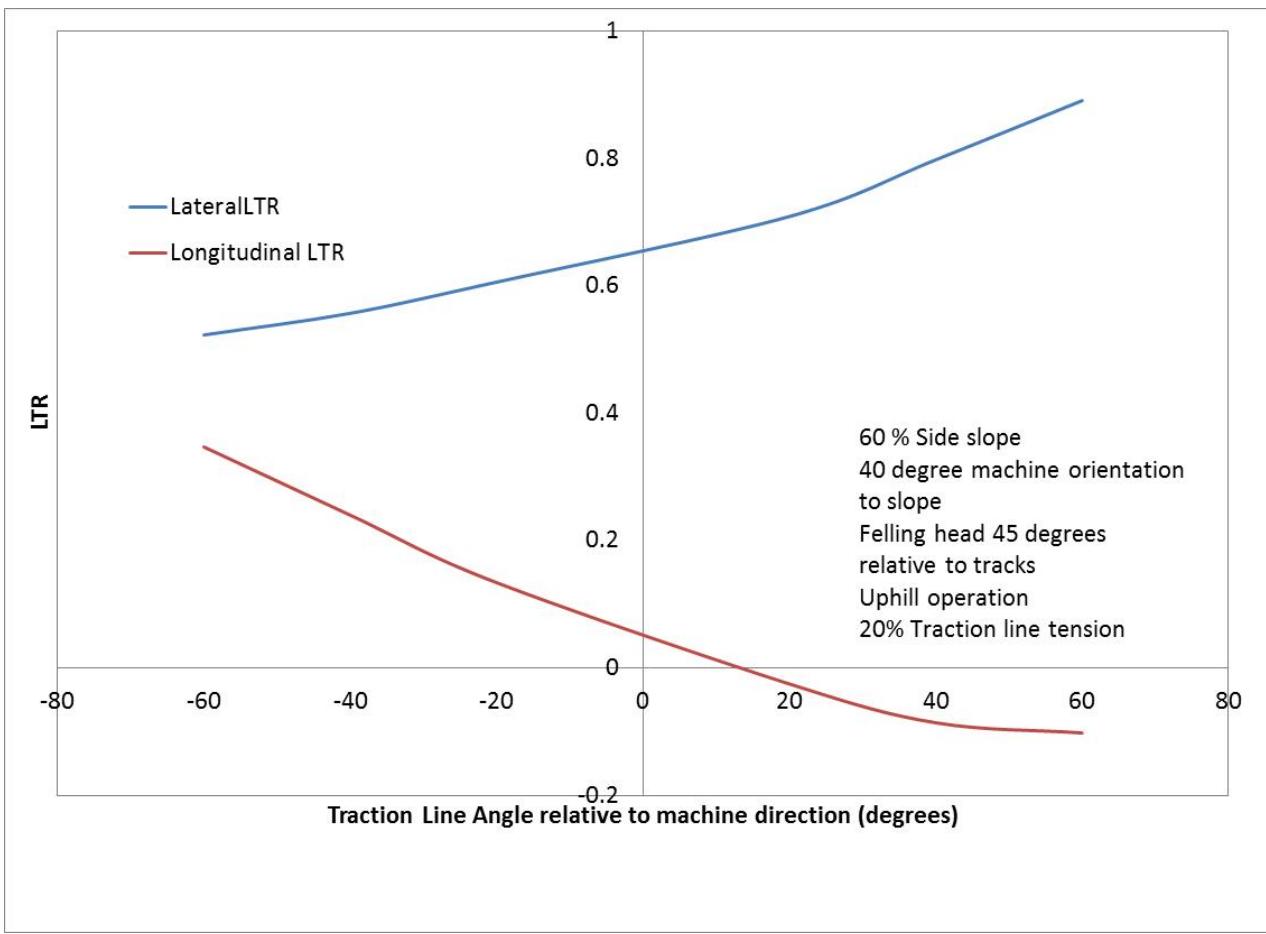


Figure 11. Traction line angle sensitivity: non-tilting machine; load 45 degrees rotated downhill.

CONCLUSIONS

A methodology has been proposed in this report that could be utilized to assist operational planners and machine operators determine suitable operability limits for steep slope harvesting applications. The findings of this study are based on simulations using FPInnovations' revised stability model. The main conclusions of this study are as follows:

- Operating in the uphill direction allows for slopes of up to 70% and 60%, for tilting and non-tilting machines, respectively, to be harvested safely with traction line tensions of 20% of machine weight.
- The operability range in the downhill direction is more limited with maximum slopes of 50% and 40% for tilting and non-tilting machines, respectively. It is likely that higher slopes could be achieved at higher line tensions. However, at these increased line tensions, the harvesting system is no longer "traction assist" for a ground surface traction coefficient of 0.5 and it becomes reliant on the traction line to support the harvesting machine.

- The operability range is generally greater for the tilting machine. However, at a machine orientation of 0 degrees to the slope, the performance of the non-tilting machine is similar to that of the tilting machine.
- Machine orientation to the slope is an important parameter to consider for steep slope harvesting. Whenever possible, minimize the machine orientation to the slope. In the uphill direction, the machine orientation to the slope should not exceed 20 degrees on slopes greater than 50%. In the downhill direction, the machine orientation to the slope should not exceed 20 degrees at slopes greater than 40%.
- Lateral stability of machines can be improved by positioning the traction line at maximum angles uphill of the machine orientation direction when the machine is not facing directly upslope. A practical guideline is to ensure the traction line is always at least facing directly upslope.

NEXT STEPS

1. The estimated operability limits prescribed in this report should be validated through field observations and discussions with users and machine manufacturers.
2. Following the validation of study results, the methodology should be revised accordingly and further analysis conducted to evaluate the effect of alternative traction levels, traction line tensions, and traction line orientation. The results of an expanded analysis could then be incorporated into a mobile app for field use.

REFERENCES

- Boswell, B., & Parker, S. (2011). *Development of a static stability test procedure for forest machines* (WorkSafeBC Contract IFP #00411 - Contract #5059). Vancouver, BC: FPInnovations.
- Boswell, B., & Parker, S. (2015). *Stability testing of conventional and tilt-cab feller bunchers* (Technical Report no. 36). Vancouver, BC: FPInnovations.
- Parker, S. (2015). *Development of a stability model for assessing machine performance on steep slopes* (BC Coastal Hem-Fir Initiative). Vancouver, BC: FPInnovations.
- Petch, N., & Parker, S. (2017). *Modelling steep slope harvesting stability through centre of gravity testing* (Technical Report no. 28). Vancouver, BC: FPInnovations.
- FPInnovations (2016). *Steep Slope Initiative*. <http://steepslopeinitiative.fpinnovations.ca/>

APPENDIX I – SIMULATION RESULTS

Table I-1. Load transfer ratio: non-tilting machine; uphill orientation; felling head directly in front of machine

Slope (%)	Machine orientation to slope (degrees)	Traction tension (% of machine mass)	Lateral load transfer ratio	Longitudinal load transfer ratio
30	0	0	0.030	-0.053
		10	0.030	-0.166
		20	0.032	-0.286
30	20	0	0.104	-0.080
		10	0.075	-0.189
		20	0.044	-0.304
30	40	0	0.221	-0.154
		10	0.162	-0.249
		20	0.101	-0.348
40	0	0	0.030	0.029
		10	0.031	-0.081
		20	0.032	-0.199
40	20	0	0.147	-0.008
		10	0.120	-0.115
		20	0.092	-0.230
40	40	0	0.300	-0.007
		10	0.244	-0.101
		20	0.185	-0.199
50	0	0	0.030	0.186
		10	0.031	0.084
		20	0.032	-0.027
50	20	0	0.195	0.148
		10	0.172	0.048
		20	0.144	-0.064
50	40	0	0.386	0.021
		10	0.335	-0.072
		20	0.265	-0.186
60	0	0	NA	NA
		10	0.032	0.167
		20	0.034	0.067
60	20	0	NA	NA
		10	0.216	0.152
		20	0.190	0.043
60	40	0	0.473	0.158
		10	0.418	0.060
		20	0.336	-0.060
70	0	0	NA	NA
		10	NA	NA
		20	0.035	0.121
70	20	0	NA	NA
		10	0.258	0.239
		20	0.260	0.133
70	40	0	0.569	0.267
		10	0.507	0.158
		20	0.410	0.035

Table I-2. Load transfer ratio: non-tilting machine; uphill orientation; felling head rotated 45 degrees downhill

Slope (%)	Machine orientation to slope (degrees)	Traction tension (% of machine mass)	Lateral load transfer ratio	Longitudinal load transfer ratio
30	0	0	0.289	0.078
		10	0.297	-0.032
		20	0.306	-0.148
30	20	0	0.416	0.045
		10	0.390	-0.061
		20	0.368	-0.172
30	40	0	0.515	-0.033
		10	0.463	-0.126
		20	0.406	-0.219
40	0	0	0.331	0.174
		10	0.343	0.070
		20	0.356	-0.042
40	20	0	0.485	0.132
		10	0.470	0.030
		20	0.454	-0.079
40	40	0	0.569	0.093
		10	0.520	0.005
		20	0.467	-0.093
50	0	0	0.350	0.308
		10	0.365	0.212
		20	0.380	0.101
50	20	0	0.548	0.253
		10	0.536	0.156
		20	0.518	0.042
50	40	0	0.699	0.156
		10	0.649	0.060
		20	0.582	-0.046
60	0	0	NA	NA
		10	0.389	0.310
		20	0.410	0.212
60	20	0	NA	NA
		10	0.584	0.269
		20	0.569	0.162
60	40	0	0.786	0.274
		10	0.732	0.164
		20	0.651	0.047
70	0	0	NA	NA
		10	NA	NA
		20	0.435	0.244
70	20	0	NA	NA
		10	0.637	0.346
		20	0.656	0.248
70	40	0	0.879	0.463
		10	0.844	0.264
		20	0.739	0.147

NA= Insufficient traction

Table I-3. Load transfer ratio: tilting machine; uphill orientation; felling head directly in front of machine

Slope (%)	Machine orientation to slope (degrees)	Traction tension (% of machine mass)	Lateral load transfer ratio	Longitudinal load transfer ratio
30	0	0	0.076	0.035
		10	0.078	-0.071
		20	0.079	-0.182
30	20	0	0.012	0.012
		10	0.007	-0.097
		20	0.002	-0.211
30	40	0	0.121	-0.063
		10	0.128	-0.180
		20	0.134	-0.299
40	0	0	0.076	0.130
		10	0.079	0.026
		20	0.081	-0.084
40	20	0	0.019	0.099
		10	0.025	-0.010
		20	0.031	-0.125
40	40	0	0.237	0.057
		10	0.248	-0.061
		20	0.258	-0.183
50	0	0	0.075	0.241
		10	0.079	0.143
		20	0.083	0.035
50	20	0	0.076	0.196
		10	0.085	0.089
		20	0.095	-0.026
50	40	0	0.351	0.118
		10	0.366	-0.001
		20	0.376	-0.132
60	0	0	NA	NA
		10	0.081	0.333
		20	0.086	0.238
60	20	0	NA	NA
		10	0.157	0.26
		20	0.168	0.143
60	40	0	0.456	0.248
		10	0.467	0.117
		20	0.472	-0.04
70	0	0	NA	NA
		10	NA	NA
		20	0.086	0.418
70	20	0	NA	NA
		10	0.228	0.453
		20	0.245	0.346
70	40	0	0.577	0.365
		10	0.578	0.228
		20	0.580	0.067

NA= Insufficient traction

Table I-4. Load transfer ratio: tilting machine; uphill orientation; felling head rotated 45 degrees downhill

Slope (%)	Machine orientation to slope (degrees)	Traction tension (% of machine mass)	Lateral load transfer ratio	Longitudinal load transfer ratio
30	0	0	0.123	0.037
		10	0.126	-0.069
		20	0.129	-0.180
30	20	0	0.183	0.013
		10	0.192	-0.096
		20	0.201	-0.210
30	40	0	0.324	-0.057
		10	0.334	-0.173
		20	0.34	-0.286
40	0	0	0.135	0.152
		10	0.139	0.048
		20	0.145	-0.062
40	20	0	0.225	0.121
		10	0.238	0.013
		20	0.251	-0.101
40	40	0	0.427	0.057
		10	0.441	-0.061
		20	0.463	-0.188
50	0	0	0.153	0.281
		10	0.158	0.184
		20	0.163	0.080
50	20	0	0.296	0.236
		10	0.313	0.130
		20	0.331	0.010
50	40	0	0.559	0.142
		10	0.577	0.023
		20	0.593	-0.152
60	0	0	NA	NA
		10	0.162	0.375
		20	0.168	0.279
60	20	0	NA	NA
		10	0.381	0.298
		20	0.404	0.174
60	40	0	0.661	0.272
		10	0.684	0.123
		20	0.689	-0.073
70	0	0	NA	NA
		10	NA	NA
		20	0.168	0.457
70	20	0	NA	NA
		10	0.433	0.476
		20	0.460	0.354
70	40	0	0.784	0.381
		10	0.806	0.204
		20	0.778	0.030

NA= Insufficient traction

Table I-5. Load transfer ratio: Non-tilting machine; downhill orientation; felling head directly in front of machine

Slope (%)	Machine orientation to slope (degrees)	Traction tension (% of machine mass)	Lateral load transfer ratio	Longitudinal load transfer ratio
30	0	0	0.029	0.836
		10	0.028	0.624
		20	0.028	0.449
30	20	0	0.167	0.809
		10	0.155	0.608
		20	0.143	0.434
30	40	0	0.290	0.719
		10	0.272	0.544
		20	0.256	0.376
40	0	0	NA	NA
		10	0.028	0.764
		20	0.028	0.551
40	20	0	NA	NA
		10	0.208	0.728
		20	0.191	0.530
40	40	0	0.381	0.845
		10	0.364	0.653
		20	0.339	0.466
50	0	0	NA	NA
		10	0.028	0.925
		20	0.027	0.676
50	20	0	NA	NA
		10	0.253	0.889
		20	0.230	0.660
50	40	0	NA	NA
		10	0.455	0.757
		20	0.417	0.576
60	0	0	NA	NA
		10	NA	NA
		20	0.026	0.795
60	20	0	NA	NA
		10	0.295	0.985
		20	0.272	0.751
60	40	0	NA	NA
		10	0.528	0.840
		20	0.485	0.644
70	0	0	NA	NA
		10	NA	NA
		20	0.026	0.946
70	20	0	NA	NA
		10	NA	NA
		20	0.312	0.874
70	40	0	NA	NA
		10	0.604	0.935
		20	0.554	0.676

NA= Unstable condition

Table I-6. Load transfer ratio: non-tilting machine; downhill orientation; felling head rotated 45 degrees downhill

Slope (%)	Machine orientation to slope (degrees)	Traction tension (% of machine mass)	Lateral load transfer ratio	Longitudinal load transfer ratio
30	0	0	0.185	0.754
		10	0.178	0.556
		20	0.173	0.383
30	20	0	0.360	0.683
		10	0.341	0.490
		20	0.326	0.319
30	40	0	0.479	0.598
		10	0.460	0.418
		20	0.436	0.244
40	0	0	NA	NA
		10	0.208	0.655
		20	0.203	0.452
40	20	0	NA	NA
		10	0.387	0.623
		20	0.361	0.426
40	40	0	0.567	0.710
		10	0.541	0.538
		20	0.505	0.346
50	0	0	NA	NA
		10	0.207	0.810
		20	0.198	0.586
50	20	0	NA	NA
		10	0.432	0.767
		20	0.401	0.563
50	40	0	NA	NA
		10	0.634	0.637
		20	0.590	0.446
60	0	0	NA	NA
		10	NA	NA
		20	0.193	0.699
60	20	0	NA	NA
		10	0.467	0.861
		20	0.437	0.630
60	40	0	NA	NA
		10	0.703	0.716
		20	0.620	0.472
70	0	0	NA	NA
		10	NA	NA
		20	0.192	0.841
70	20	0	NA	NA
		10	NA	NA
		20	0.475	0.767
70	40	0	NA	NA
		10	0.788	0.827
		20	0.709	0.505

NA= Unstable condition

Table I-7. Load transfer ratio: tilting machine; downhill orientation; felling head directly in front of machine

Slope (%)	Machine orientation to slope (degrees)	Traction tension (% of machine mass)	Lateral load transfer ratio	Longitudinal load transfer ratio
30	0	0	0.074	0.673
		10	0.072	0.502
		20	0.070	0.349
30	20	0	0.161	0.693
		10	0.149	0.521
		20	0.138	0.367
30	40	0	0.289	0.650
		10	0.273	0.489
		20	0.257	0.346
40	0	0	0.076	0.720
		10	0.072	0.532
		20	0.068	0.371
40	20	0	0.214	0.739
		10	0.189	0.541
		20	0.177	0.382
40	40	0	0.402	0.715
		10	0.378	0.549
		20	0.357	0.380
50	0	0	NA	NA
		10	0.071	0.680
		20	0.068	0.493
50	20	0	NA	NA
		10	0.267	0.640
		20	0.247	0.457
50	40	0	0.539	0.656
		10	0.519	0.469
		20	0.485	0.295
60	0	0	NA	NA
		10	NA	NA
		20	0.067	0.662
60	20	0	NA	NA
		10	0.330	0.853
		20	0.304	0.653
60	40	0	NA	NA
		10	0.642	0.618
		20	0.583	0.436
70	0	0	NA	NA
		10	NA	NA
		20	0.067	0.854
70	20	0	NA	NA
		10	NA	NA
		20	0.356	0.768
70	40	0	NA	NA
		10	NA	NA
		20	0.820	0.630

NA= Unstable condition

Table I-8. Load transfer ratio: tilting machine; downhill orientation; felling head rotated 45 degrees downhill

Slope (%)	Machine orientation to slope (degrees)	Traction tension (% of machine mass)	Lateral load transfer ratio	Longitudinal load transfer ratio
30	0	0	0.274	0.487
		10	0.268	0.331
		20	0.261	0.182
30	20	0	0.359	0.507
		10	0.344	0.348
		20	0.330	0.200
30	40	0	0.491	0.459
		10	0.476	0.310
		20	0.458	0.169
40	0	0	0.262	0.539
		10	0.253	0.366
		20	0.245	0.212
40	20	0	0.396	0.559
		10	0.368	0.372
		20	0.351	0.219
40	40	0	0.594	0.522
		10	0.566	0.361
		20	0.537	0.196
50	0	0	NA	NA
		10	0.251	0.519
		20	0.294	0.339
50	20	0	NA	NA
		10	0.439	0.470
		20	0.414	0.298
50	40	0	0.709	0.465
		10	0.683	0.282
		20	0.634	0.097
60	0	0	NA	NA
		10	NA	NA
		20	0.238	0.513
60	20	0	NA	NA
		10	0.499	0.672
		20	0.465	0.472
60	40	0	NA	NA
		10	0.792	0.444
		20	0.763	0.240
70	0	0	NA	NA
		10	NA	NA
		20	0.235	0.685
70	20	0	NA	NA
		10	NA	NA
		20	0.515	0.610
70	40	0	NA	NA
		10	NA	NA
		20	0.920	0.450

NA= Unstable condition



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