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Determining Facial Validity of a Forest Harvest Simulation

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Abstract

Forest harvest simulations provide an opportunity for the forest engineering community to design and evaluate harvesting operation equipment on desk computers under variable terrain, environmental, and economic constraints. This capability influences the effectiveness of harvest unit design in office environment. When designing harvest units for ground-based harvesting systems, it is important to incorporate challenging design parameters that reflect real-world practice. Therefore, the facial validity of forest harvest simulations is critical when used for educational purposes. This study compared the performance limits of the cut-to-length machines in the simulator system with those provided by expert operators in the State of Oregon to determine the facial validity of forest harvest simulations in the John Deere harvesting simulator system. We considered whether the slope mobility and reach limits of the simulated machines are sufficiently similar to the expert defined limits to be educationally useful. Though the simulator has stability limits that are potentially greater than the real machine when operated by an expert operator, the findings indicated that the simulator is sufficiently similar to the real machines. Specifically, the 30% adverse, 40% favorable, and 15% side slope expert limits are considered facially valid for harvest plan development. Additionally, the expert operator in the simulator system operated between 4m to 11m away from the mast of the machine, supporting the conclusion that the forest harvest simulation is facially valid regarding reach and trail spacing.

Keywords: Harvester simulator, Trail spacing, Harvest unit design, Forwarder slope limits, Harvester reach limits.

1. Introduction

A forest harvest simulation is a 3-dimensional representation of the harvest unit, including roads, streams, trees, and slopes (Lapointe & Robert, 2000), generated by a computer algorithm that models real-world systems and processes (Deshpande and Huang, 2011). People interacting with simulated environments can experience them as resembling reality (i.e., facial validity) (Dole and Ju, 2019); however, this does not mean the underlying algorithms generating the simulation are faithfully reproducing real-world physics. What is important in the simulation is that the representation, or its closeness to reality, is useful for the activity being performed under typical operating conditions and that it elicits task performance intuition (Dole and Ju, 2019). The facial validity of a forest harvest simulation for an educational application lies in whether the simulation output captures the essential features of the real environment and can elicit practical actions from the people performing the activity (Harris et al., 2020). In this context, a facially valid simulation is the one that is sufficiently close to reality be used to train forest engineers in harvest unit design.

The John Deere harvester simulator system uses the actual harvester machine controls mounted on a desktop computer, with the simulation display on a screen. The simulator has a terrain editor interface that allows users to simulate a 3D forest harvest unit of their choice using inventory and map data, and to add features and objects, such as machines to simulate logging. The simulated environment is a useful tool for equipping forestry harvesting professionals with knowledge through comprehension, reflection on task performance methods acquired over time, and experiential learning (Kolb, 1984). The simulated environment can shape perspectives of the people interacting with it, enabling the development of interactions and the consideration of tradeoffs (Miltiadou and Savenye, 2003).

The simulated environment, when used in education, should represent basic elements of the real world that can influence user immersion and presence, shaping user

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behavior in ways similar to those encountered in the actual task environment to achieve specific task outcomes (Harris et al., 2020). The simulated environment used for educational purposes, therefore, should facilitate transfer of training where the user is able to adapt and recognize elements related to specific tasks and apply residual knowledge, skills, and experience to perform related tasks. Harris and others (2020) proposed a method for validating a simulated environment used in educational training, in which the results of the simulation should reflect the description of a realistic object, process, or system, complete with elements that the subject sees as preassembling task reality. This facial representation of elements is what the subject interacts with when performing a task and, as such, represents what the subject perceives as real, and the subject makes tasks decisions depending on the degree of challenge presented by the task. The simulated environment should also closely match the real environment in terms of measurement accuracy to provide subjects performing the experiential activity with the opportunity to transfer learning (Harris et al., 2020). For example, the motion of the simulated machines in the simulator system should reflect the actual motion of the equipment when performing its functions under real task conditions.

When designing a harvest unit for a mechanized ground-based cut-to-length (CTL) harvest method that uses a combination of harvester and forwarder, it should be noted that their mobility is constrained by terrain slope (Cavalli & Amishev, 2019; Stampfer, 2016). Visser and Stampfer (2015) report that this combination is productive on terrain slopes ranging between 0% and 40%. Notably, harvest unit design should consider that the capability and limitation of a harvester and a forwarder are dependent on their functional design (e.g., articulated frames, high ground clearance, wide wheelbase, and high torque) that influences their stability, ground traction, and power during harvesting tasks (Gibson et al., 1971). The machines become unstable when at least one of the tires lift off the ground or slipping and tipping over during task performance (Sessions, et al., 2016). When driving across a slope and turning uphill, the articulated frame shifts the center of gravity to the downhill side, thereby reducing machine stability (Adams, 1959; Gibson et al., 1971). Belart et al. (2019) also reported that machine stability on steep slopes is a function of traction, and since traction is dependent on soil moisture and shear strength, variability in soil moisture contributes to traction loss on steep slopes. Therefore, in the design of forwarding trails, the ability of a forwarder to move uphill is limited by traction, stability, and power. When moving on a side slope, losing traction, or encountering obstacles can rapidly destabilize the forwarder, increasing the risk of rollover and slipping that have the potential to damage the machine and endanger the operator. A harvester machine can be deployed on a range of slopes; for example, Visser and Stampfer (2015) noted that a harvester can operate on slopes up to 60% if stability and traction are maintained. However, no studies have reported the reach limits of a harvester, which is important for determining trail spacing. This study considered reach limits of the simulated John Deere 1270 harvester and the 1510 forwarder to assess the validity of simulations for training forest engineering in harvest unit layout within a simulated environment. The study also compared the performance of the simulated machines with operational limits recommended by expert operators to provide guidance for laying harvest unit trails when designing a forest harvest unit using forest harvest simulation.

2. Materials and Methods

2.1. Slope Limits Data Collection

Determining the appropriate slope limit for a harvester and forwarder combination requires an understanding of individual machine capability on slopes. The revised WorkSafeBC guidelines (2011) specify operational limits for machines on steep slopes under as follows: i) a rubber tired skidder must not be operated on a slopes exceeding 35%, ii) a crawler tractor, feller buncher, excavator, and similar equipment must not be operated on slopes exceeding 40%, and iii) any other forestry equipment specifically designed for steep slope must not be operated on a slopes exceeding 50%. Logging industry experts in Oregon identified slope limits for a forwarder as 30% for adverse slope, 40% for favorable slopes, and 15% for side slope. Visser and Stampfer (2015) indicated that mechanized ground-based machines are commonly deployed on slopes ranging from 0% to 40%. A loaded forwarder is heavier and has a higher center of gravity than a harvester. In the CTL system, the forwarder serves as the limiting machine due to its mobility constrains.

Forwarder slope limits test runs were designed for the John Deere forwarder 1510 model, which is built into the John Deere harvester simulator. The facial validity test for the forest harvest simulation was based on the adverse, favorable, and side slope limits provided by the industry expert. Three uniform terrain slopes of 20%, 30%, and 40% slopes were generated using the John Deere Terrain Editor 4 (John-Deere, 2022). There were five directions of travel measured in degrees along trails marked on the uniform slopes: i) 90^0 degrees uphill direction (perpendicular to the contours), ii) 45^0 degrees direction on terrain uphill, iii) 0^0 degrees direction (parallel to the contours or side slope), iv) 315^0 degrees direction on downhill terrain, and v) 270^0 degrees direction downhill (perpendicular to the contours). Three different rock sizes were placed 20m apart along each trail to act as ground obstacles: i) 0 cm rock (e.g., no rock), ii) 25cm rock, and iii) 40cm rock to simulate obstacles for the forwarder. There were four loading scenarios: i) $9m^3$ load, ii) $12m^3$ load, iii) $15m^3$ load, and iv) $18m^3$ load. Figure 1 shows a simulated scenario with

uniform terrain slope, highlighting the five directions of travel and rock obstacles.

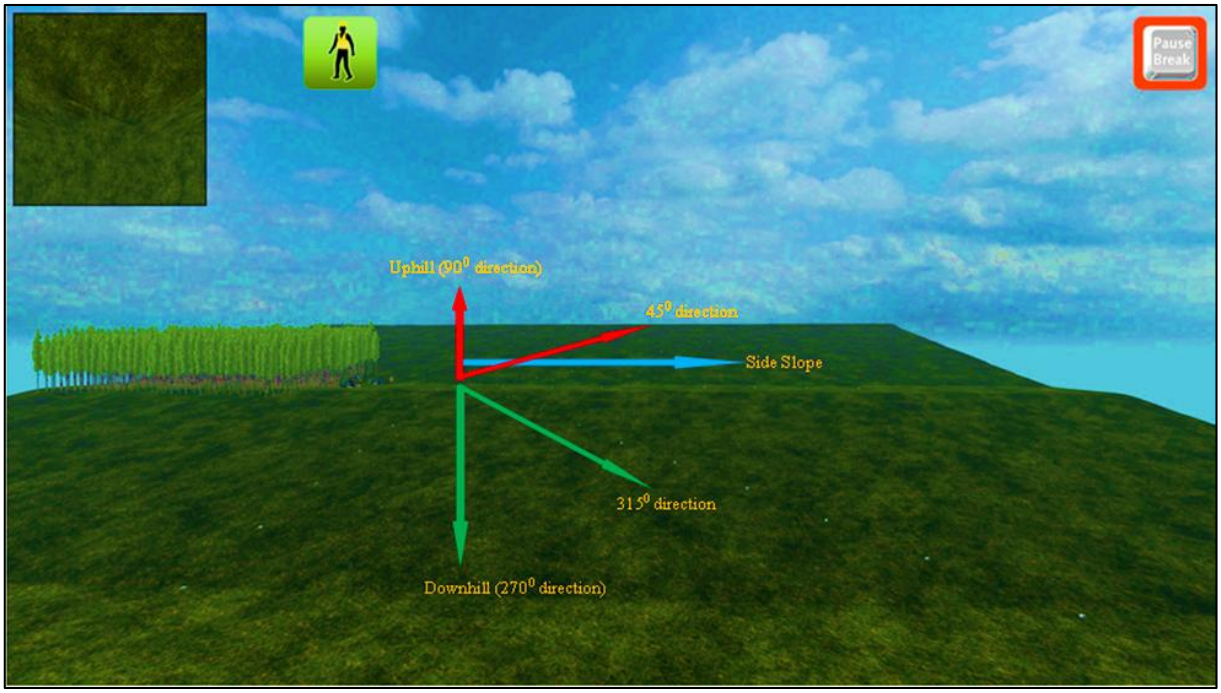


Figure 1 Slope simulation showing direction of travel in angles

The mobility scenarios are defined by slope, travel direction in degrees, rock size, and forwarder load. For example, in scenario 20452512, 20=20% slope, 45=45^0-degree direction of travel, 25=25cm rock size, 12=12m^3 forwarder load). During the test runs, a scenario was selected, and the forwarder made three attempts to drive along the path with one wheel path running over the rock obstacles. The success of an attempt was defined as the forwarder completing the test run without any difficulty. Failure of an attempt was defined as the forwarder completing the test run with difficulty (i.e., temporary slipping or tipping) or the forwarder not completing the test run. Failure modes were recorded as i) lack of power (i.e., machine not moving forward), ii) lack of traction (i.e., at least one wheel slipping), and iii) instability (i.e., at least one wheel lifting off the ground).

2.2. Reach Limits Data Collection

The ability of a harvester to access trees allocated at a distance from the trail and deck logs within the reach of the forwarder positioned on the trail is key factor limiting trail spacing. During the layout process, the adjustable parameters include the maximum distance the harvester can reach trees and extent to which it operates off the trail. The reach of the harvester is defined as the distance from the mast to the falling head. The John Deere 1270 has a maximum reach of 11.7m from the trail (John-Deere, 2022). The operational reach of the harvester depends on the length of its crane (including boom, stick and telescope), terrain slope, and direction of travel. The maximum accessible distance for a tree from the trail is determined by both the harvester's reach and its offset from the trail. In this context, a harvester reach is defined as the distance between the mast and the tree being cut when the harvester is positioned on a trail, while the distance off the trail is the perpendicular distance from the mast to the center of the trail (Figure 2). Harvester reach data was collected by observing videos of an experienced operator working in a simulated environment with the John Deere harvester 1270 model and recording the distance measurement displayed on the simulator monitor for two points selected on the screen while the harvester is cutting trees along the trail in the following simulated video scenarios:

i) reaching trees from a trail on a flat bench
ii) reaching trees at a long corner while working off the trail
iii) reaching trees while moving up a steep slope
iv) reaching trees while moving down a steep slope

In this study, reach limit data were obtained by placing the cursor on the simulator monitor display at the base of the mast, carefully moving it to the point where the tree is cut by the harvester head in the simulated harvesting video, and clicking it again. The perpendicular distance from the mast to the tree was measured as the distance between the two points clicked by the cursor on the simulator monitor screen and recorded by the researcher as the reach distance from the trail to the tree. This action was repeated, and harvester reach data were recorded for every tree that was cut by the harvester in each simulated harvesting scenario (i) to (iv) above.

Three groups of experts examined the facial validity of the simulated forest harvest environment. The limits used in the forwarder slope simulation were provided by a logging expert with over twenty years of industry

experience in trail design and served as a criterion for determining the initial planning limits for the logging plan. The forwarder slope limits provided by the expert were used for simulation scenarios conducted by the researchers in this study. The expert operator who ran the simulated harvester is an experienced logging industry machine operator in the state of Oregon.

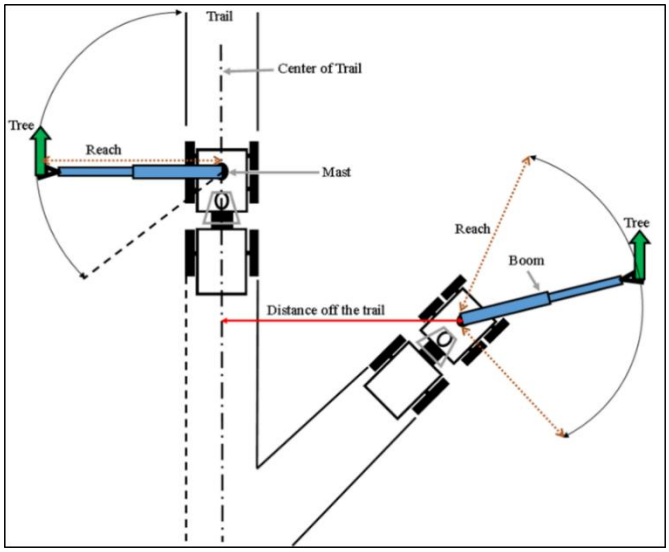


Figure 2 Harvester sitting on a trail and off the trail

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3. Validation of the map

3.1. Slope Limits

The outcomes of the John Deere forwarder 1510 test runs are reported for three directions of travel: 90^0 degrees (adverse grade), 270^0 degrees (favorable grade), and 0^0 degrees (side slope). In the summary grid presented in Figure 3, the following categories are defined: i) *All observations Successful,* indicating that all three test runs were completed successfully, ii) *At least one successful run with difficulty,* indicating that at least one test runs was completed with difficulty; and iii) *No Successful Observation*, indicating that none of three test runs were completed.

Results show that test runs with an $18m^3$ load, 40cm rock on a 20% adverse grade were successful, while runs with a $12m^3$ load, 0cm rock on the 30% or 40% adverse grades failed. Forwarder runs with $9m^3$ load, 0cm rock on the 30% adverse grade were successful, while that of the same load on 40% adverse grade failed. Forwarder runs with $18m^3$ load, 40cm rock on a favorable grade were all successful. Runs with $18m^3$ load, 40cm rock on 20% side slope were all successful. Test runs with up to $15m^3$ load, 40cm rock, on 40% side slope were successful, while those with $18m^3$ load, 40cm rock on 40% side slope failed. Failure due to non-completion of runs mostly occurred on adverse grade, while at least one run was completed on side slope with difficulty.

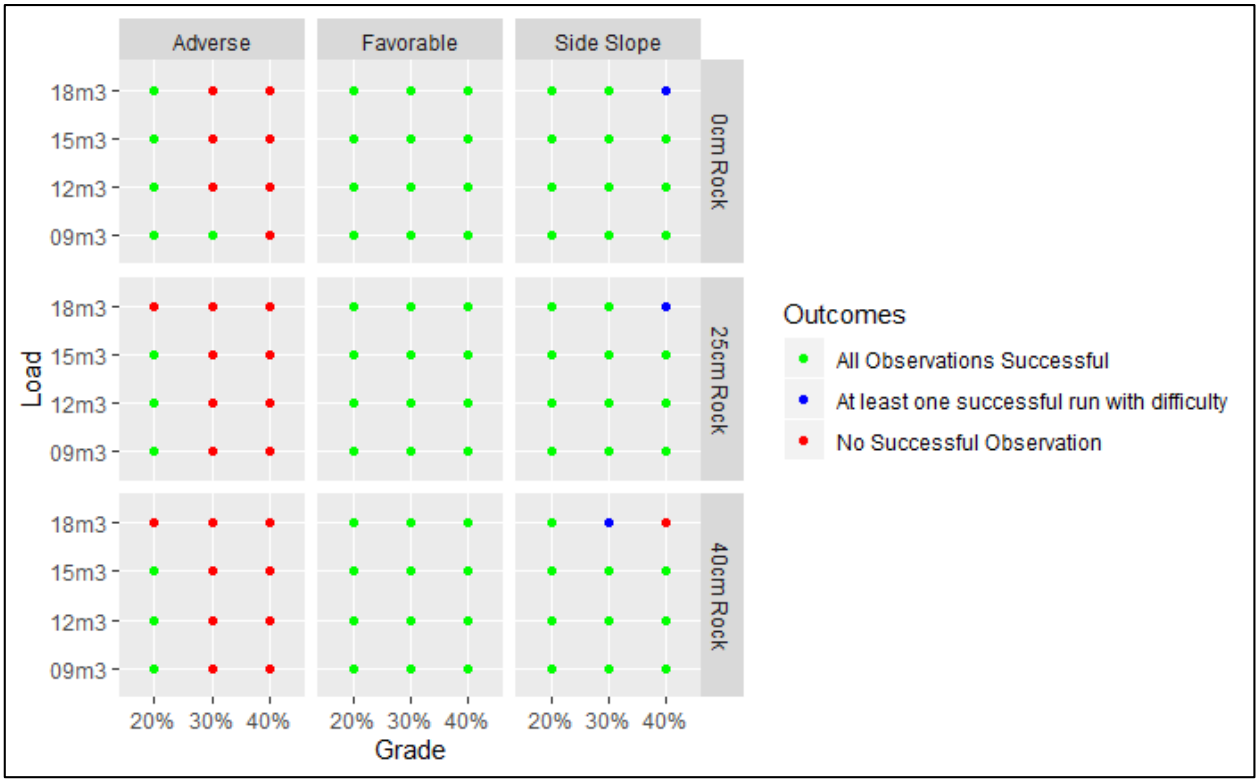


Figure 3 Outcomes for forwarder test runs where 900 direction of travel (adverse), 2700 direction (favorable), and 00 direction of travel (side slope).

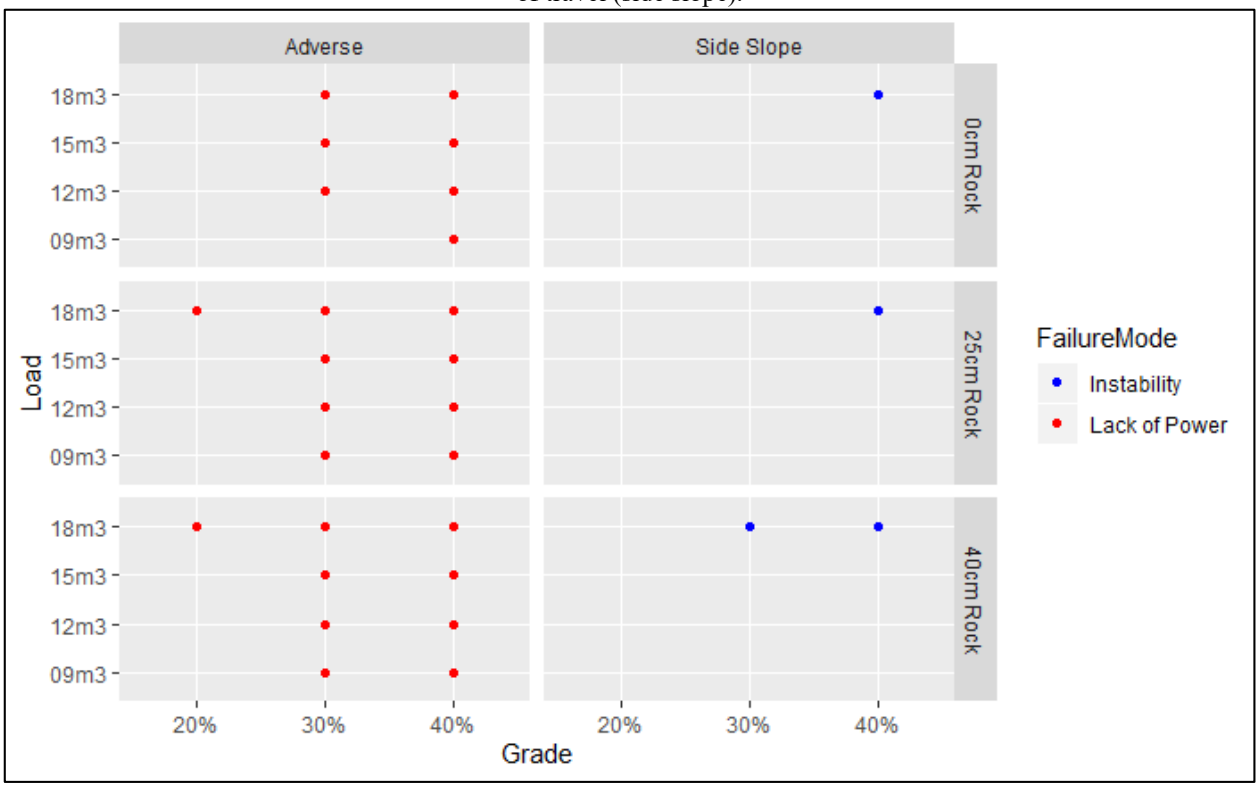


Figure 4 Failure mode by direction of travel where, 900 (adverse), and 00 (side slope)

Table 1 compares simulator performance to the trail slope limits suggested by experts. In Table 1, a simulator meeting the expert limit (e.g., a “Yes") means that the simulator performed and, in some cases, exceeded the performance limits given by the expert from the logging industry.

Table 1. Expert values for forwarder trails as compared to the simulated performance

Direction of travel	Expert value	Simulator meets expert limits (Y/N)	Explanation
Favorable	40%	Yes, expert limit exceeded	• All observations were successful at a 40% favorable grade, with no simulator limit. • There was a tip over while traveling at 315^0 degrees on a 40% terrain slope.
Adverse	30%	No, expert limit not achieved	• The limit for $18m^3$, 0cm rock is 20% grade • There was a lack of power with loads greater than $9m^3$ and 25cm rock on 30% adverse grade. • There was no successful observation at 40% adverse grade
Side slope	15%	Yes, expert limit exceeded	• All runs are successful with an $18m^3$ load, 0cm rock, and 20% side slope. • The forwarder tipped over while travelling on a 30% side slope with $18m^3$ load and 40cm rock. • The forwarder tipped over while travelling on a 40% side slope with an $18m^3$ load and 0cm of rock.

3.2. Reach Limits

The maximum design length of the harvester crane (i.e., boom, stick, and telescope) was 11.7m. Analysis of the expert operator videos indicated that the harvester reached trees located up to 11.3m from the mast (Figure 5). Most observed reach were clustered near the maximum design limit. Additionally, the results demonstrated that the expert operator targeted only trees located more than 4m from the mast.

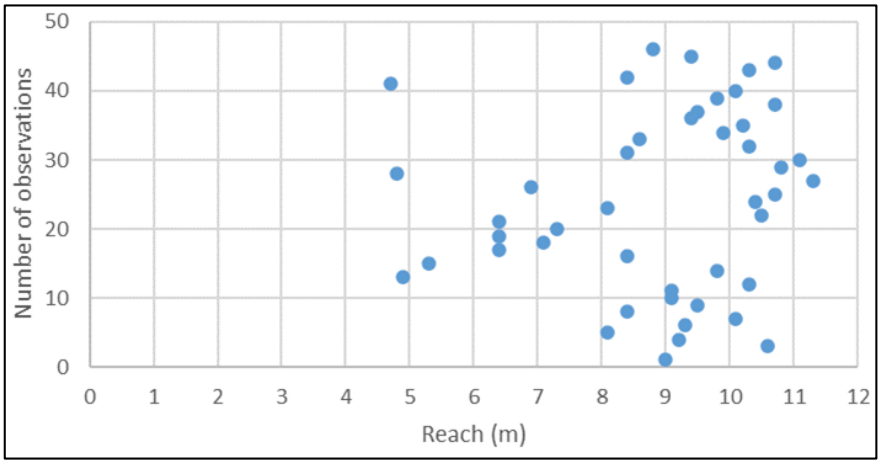


Figure 5 Harvester reach data determined from the simulated videos

When working off the trail, the expert operator positioned the harvester at distances between 12m and 16m from the mast located at the center of the trail (Figure 6). This placement enabled the operator to swing logs back to locations accessible to the forwarder operating from the trail. The operator deliberately avoided targeting trees within 11.7 m of the trail, as these could be readily accessed by the harvester when positioned on the trail.

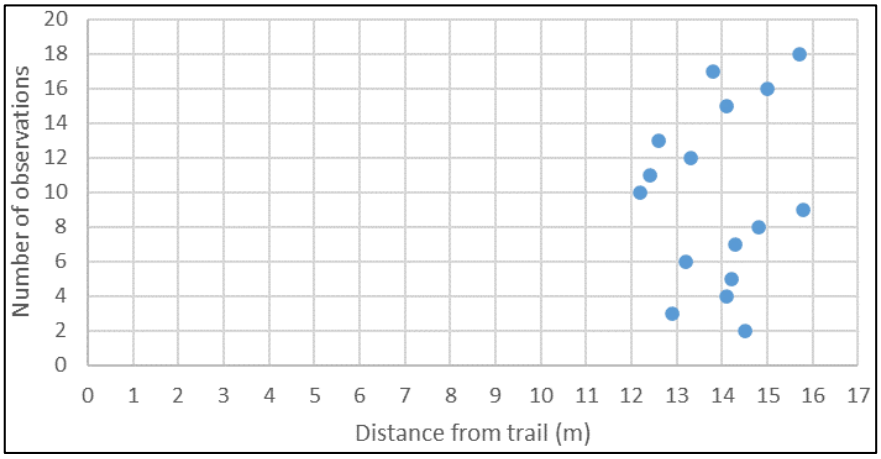


Figure 6 Harvester distance from the mast to trail determined from the simulated videos

4. Discussion

Forest engineers are known to have boots on the ground to verify site characteristics that determine which logging methods to apply. However, limited research has evaluated the suitability of computer simulations for logging planning. Using computer simulation to prepare logging plans can help minimize environmental impacts and safety concerns associated with site visits, reduce on-site planning costs, and usher in a new era of logging planning through forest harvest simulations.

When operating a machine in the real world, failure mode is an important consideration for mobility. When traveling on an adverse grade, failure is due to lack of power or loss of traction; the machine is unable to move forward. This is not an immediate safety hazard as the machine is stationary. However, when traveling on a favorable grade and failure is due to slipping, the machine continues to accelerate until the grade decreases or stops when it hits an obstacle. This finding is consistent with the results reported by Cavalli & Amishev (2019) and Stampfer (2016), who observed that terrain slope limits machine mobility on adverse slopes.

Sessions et al. (2016) note that machine becomes unstable when at least one tire lifts off the ground, leading to tipping. The condition of uncontrolled slipping is an immediate safety hazard, and the onset of sliding is sudden. Thus, a safe operator will be very conservative when setting an allowable favorable grade to ensure uncontrolled sliding does not occur. When traveling on any grade and failure is defined as loss of stability (tipping over), the machine is beyond the point of failure and unable to recover. Tipping a machine over is an immediate safety hazard, and the point of instability occurs suddenly. Thus, a safe operator will be very conservative when setting an allowable side slope limit for a forwarder trail. The forwarder simulation is facially valid for adverse trails and close for favorable trails (particularly those with combined side slope and grade). Thus, the expert allowable limits of 40% for favorable trails and 30% for adverse trails are appropriate and facially valid for guidance in the design of a harvest unit. This result aligns with the findings of Visser and Stampfer (2015) who report operational stability for

forwarder and harvester machine on slopes up to 40%, and with slope limits provided by WorkSafeBC (2011).

The simulated machines can travel low-grade trails with side slopes much higher than those recommended by expert operators. This discrepancy may result from operators exercising caution due to the severe consequences if a potential tip over occurs, as well as the sensitivity of the machine to destabilizing accelerations caused by pneumatic tires interacting with obstacles. The appropriateness of adjusting the limits used in harvest unit design warrants consideration. Side slope travel is an important limiting factor for wheeled ground-based harvesting equipment. If side slope limits are not set conservatively during harvest unit designing, the resulting plans may prove infeasible in practical applications, thereby diminishing the value of the design process. Thus, continued use of the 15% side slope limit recommended by experts is supported as a valid guideline for harvest unit designing. This finding falls within the observed operational limits reported by Visser and Stampfer (2016) for most ground-base systems, which operate on slopes ranging from 0% to 40%. It is also important to note that machine mobility on a side hill, particularly when loaded and travelling on adverse grades or negotiating corners, is further constrained during movement and when picking up loads at full reach, as noted by Sessions et al. (2016).

Harvester reach is a function of the length of the crane (boom, telescope, and stick) and operator's decision; for example, where to locate the trail and how far from the trail to position the harvester to achieve maximum harvester productivity. In the expert videos, the observations made for reach are consistent with the design limits of the harvester. A combination of grade and side slope, location of tree from trail, and direction of crane determined how far the expert operator could reach from the trail. Trail spacing was found to depend on the maximum forwarder reach from the trail, the time required to swing logs to a location accessible by the forwarder, and the direction of travel on steep slopes. For example, when trees were located beyond 21m from the trail, the harvester required additional time to swing logs back to the position accessible to the forwarder. Since harvester productivity is a time function (Acuna and Kellogg, 2017) and swinging logs at longer distances while operating off the trail takes considerable amount of time that impacts on harvester productivity. Analysis of harvester reach data from the expert videos supports the facial validity of the harvester's reach, and the recommended tree-to-trail distance of 11 meters when on the trail, and a maximum of 22 meters when off the trail, are reasonable and valid for harvest unit design. The reach limits reported in this study provide a foundation and methodology for planning harvester trails and for determining maximum trail spacing through forest-harvest simulation. However, the reach limits are specific to John Deere 1270 harvester and should be used as a guide when determining maximum reach limits and trail spacing for other John Deere harvester models.

5. Conclusions

The forwarder trail limits provided by an expert operator were 40% favorable, 30% adverse, and 15% side slope. When running the simulated forwarder along trails with a uniform adverse grade and 0% side slope, the 30% adverse limit was apparent when 25cm rocks were included on the trail. When running the forwarder along trails with a uniform favorable grade and 0% side slope, the favorable limit of 40% was not apparent; however, once a side slope was included in the trail, along with a steep grade, the forwarder quickly became unstable. Since the simulator was tested on up to 40% terrain slope, there is a possibility of obtaining different results with slopes greater than 40%. When running on a horizontal trail, the 15% side slope limit was not apparent, even with rocks added to the trail. The stability threshold is particularly dangerous because if it is exceeded, there is no way for the operator to recover, and rolling over can result in severe machine damage and injuries. Given real-world problems, it is understandable that an operator would use conservative rollover.

The expert operator who ran the simulator for the experiential learning activity commented that the simulated machine handled similarly to the real machine. The expert operator ran the simulated machine as he would in real life using strategies he had built up through experience. The operator was used to running the machine conservatively and continued to do so in the simulated environment. Though the simulator has stability limits potentially greater than those of the real machine, we conclude that when the simulator is operated by an expert operator, it is sufficiently similar to the real machine, and that the slope limits provided by the expert operator are suitable and facially valid for harvest unit design using a forest harvest simulation.

The harvester reach limit provided by the John Deere equipment manufacturer is 11.7m. When working from the trail, the expert operator who ran the simulated harvester targeted trees within 11.7m reach from the mast. It is important to note that trees within this distance fall within the recommended reach limits provided by the John Deere. When positioned off the trail, the expert operator kept the mast's distance from the trail below 17m. While considering the maximum reach distance for the harvester provided by John Deere company and the reach and maximum of the mast from the trail from the expert operator, we conclude that the 11m reach and 22m maximum distance from the trail are sufficiently similar to those of a harvester working in the real world and facially valid for a harvest unit design using a forest harvest simulation. We conclude that the slope and reach limits investigated in this study are sufficiently valid for designing trails for a harvest unit designed for John Deere harvester 1270 and a forwarder 1510 models.

Future research should focus on implementing forest harvest unit plans designed using forest harvest simulation for validation, as this would help minimize costs associated with manual unit layout and ensure the operational safety of personnel involved in physical unit layout.

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