Analysis of How Forwarder Operators Change their Speed throughout the Harvest Area

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Executive Summary

A forwarder operator travelling around the harvest area will continuously change speed to suit the terrain. To successfully transition from traditional forwarders to autonomous forwarders, a speed control system will need to be developed (to find the appropriate speed, acceleration and deceleration of the forwarder). This study will focus on the how the forwarder changes its speed throughout the harvest area. To find this out we must first categorise the different types of terrain a forwarder travels over, taking into consideration the obstacles along the path, and whether the forwarder was loaded or unloaded.

A GPS was attached to the roof of the forwarder to measure the time and the distance travelled. A GoPro was attached to the front of the forwarder to view the direction of its path. Data used to measure the speed, acceleration and deceleration was collected from three different sites. This enabled the average speed data to be calculated for each scenario. Each scenario includes:

- The category of terrain,
- Any obstacle that was in the forwarders path, and
- If the forwarder was loaded or unloaded.

Trials took place at Mayfield, Stillwater, and Balmoral Forest respectively, with each site having a different operator and forwarder. The average speed travelled when loaded vs. unloaded had very little change in speed (0.3 km/h), as suggested by Visser et al., (2017). The speed of a forwarder continually changed to suit the terrain of the harvest area. The average speed on the landing and smooth track was the fastest (between 4.9 and 5.3 km/h). The average speed on the rough track was 3.7 km/h while loaded, and 3.9 km/h while unloaded. The cutover was the slowest terrain category with an average speed of 3.3 km/h while loaded and 2.9 km/h unloaded.

Acceleration from a stop, and deceleration to a stop both had similar values between 0.12 and 0.13 m/s^2 regardless of if the forwarder was loaded or unloaded. However values were much smaller (between 0.05 and 0.07 m/s^2) while decelerating towards an obstacle, and accelerating away from the obstacle, regardless of if the forwarder was loaded or unloaded.

The study conducted is the first of its kind, resulting in the alteration of the method throughout the process. The final results show good preliminary values that could be used as an estimate when building a speed control system for an autonomous forwarder. However, to fully build a speed control system suitable to operate in the harvest area, further investigation is required into how a forwarder travels under different conditions and environments.

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Introduction

The New Zealand forest industry continues to grow with increasing harvest volumes each year. For companies to keep up with increasing harvest volumes, more efficient harvesting methods need to be looked into, while still maintaining a high level of health and safety. Current practices see Forwarder operators travel to the harvest area to collect logs that have been felled and bunched into smaller stacks. The forwarder will travel to the log stacks to load until enough logs have been accumulated to travel back to the landing. Once at the landing, the operator will unload the logs according to log grade and then repeat the same process.

To remove the repetitive task of operating a forwarder, a team of mechanical and mechatronics (mech.) engineering students are designing and building an autonomous forwarder model. A forwarder operator working on site will continuously change their speed to suit the terrain. To integrate an autonomous forwarder into the forest safely, it must be able to assess the terrain and obstacles around it using sensors and computing software. Once the surrounding terrain has been scanned and categorised, the forwarder will adjust its speed accordingly.

Time studies have previously been conducted on the average speed of a forwarder in the harvest area, though this does not assess the terrain at each point of the forwarders cycle. Having an Increased understanding of how a forwarder operator drives around the harvest area would enable a speed control system to be developed for an autonomous forwarder that is safe, whilst maintaining an efficient output. Data collection will involve a GPS to measure the speed of the forwarder, and a GoPro to help identify any obstacles that are present in the harvest area.

Literature Review

Introduction to forwarders

Forwarders are used for mechanised ground-based harvesting to transport logs from the cutover to the landing (Table 4). Forwarders have the capability to cart stems, although they typically extract logs that are cut-to-length. They have a low environmental impact and large load capacity when compared to other ground-based extractions systems such as the grapple skidder. The forwarder has an optimal extraction distance range of 200-600 meters (Strandgard et al., 2017). The extraction distance is measured as the distance travelled between where the first log is loaded on to the forwarder, and the first log is unloaded on the landing.

The extraction distance consists of numerous types of terrain ranging from the landing, rough tracks, smooth tracks and the cutover. Forwarders are suited to flat and rolling terrain (<15%) that often have low cost and high volume outputs. The extraction method involves picking up stacks of initial graded logs and transporting them back to the landing for further grading and quality control. The logs are loaded with the coordination of the log grade so they can be unloaded more efficiently into their respective stacks on arrival at the landing.

Autonomous forwarder background information

Driving over rough terrain can causes whole-body vibrations, potentially leading to severe health problems such as muscle fatigue (Tiemessen et al., 2007). Whole-body vibration is a common health problem in many industries that results in both short and long-term side effects. Whole body vibration is a direct result of sudden jolts including rapid changes in vehicle speed, load release, and abrupt stops (Waters et al., 2007). Fatigue can affect the operator's performance through environmental, human, and task factors.

Implementation of autonomous vehicles has been successful in other industries such as mining and agriculture, while also coming under some social issues (Brown, 2018). Improving productivity and reducing the costs of harvesting is a common goal of harvest managers. Autonomous vehicles are capable of doing the same work as a skilled driver, as well as the added benefits of reduced human error and inefficiencies (Hamada & Saito, 2018).

The mech. students have been given the opportunity to design and build an autonomous forwarder prototype that can navigate between two given points and recognise any obstacles in the way. The forwarder prototype in Figure 1 is aiming to be used as a proof of concept that autonomous machines can be developed and implemented into the forest environment.

Figure 1: Autonomous forwarder prototype being developed by the mech. team

Speed control system background information

To integrate an autonomous machine successfully into the forest, sensors will need to be able to differentiate between the categories of terrain and obstacles that are ahead so the speed can be changed to suit. Selecting a speed too fast for an autonomous vehicle can cause problems such as side slips, tip over, or separation between the vehicle and ground (Shiller and Gwo, 1991) while selecting a speed too slow could potentially reduce harvest productivity and become a bottleneck of the operation (Goldratt and Cox, 2004).

Although forwarders are built strong, there is a direct correlation with how aggressively operators drive them, and the number of breakdowns the forwarder has (Russell, Lee, & Grant, 2018). Fatigue failure is the tendency of a material to fracture through progressive use and everyday stresses that occur far below the normal strength of the material (Roylance, 2001). Vehicles under loads come under fatigue when driving over uneven terrain or have abrupt accelerations. Fatigue cracks can quicken due to the way machines are operated or programmed. Components that fatigue would affect in a forwarder include the suspension, steering system, driving hubs, and structural welds (Bedkowski, 2014).

The speed a forwarder travels is restricted by the surrounding terrain, with the cutover having obstacles that are often covered by slash (Tiernan et al., 2004). Slash piles up to one meter tall can usually be travelled over with ease, although according to operators (Russell, Lee, & Grant, 2018) logs located near the top of the slash pile can cause damage to the forwarder, so should be avoided where possible.

A forwarder in Italy travels at less than 2 km/h for 77% of the time, while travelling faster than 12 km/h for only 3% of the time. The same study also looked into the terrain being travelled over a site, with 42% of the distance being on forest roads, and a similar 43% of the distance being off-road. The remaining 13% of travel time was on a sealed road (Spinelli et al., 2015). The speed a forwarder travels when loaded compared to unloaded is only minor according to the data collected in two sites (Visser et al., 2017). Table 1 shows the average speeds of A John Deere 1110D on Site A and a John Deere 1010D on Site B, with the two forwarders travelling loaded and unloaded on each site.

Table 1: Mean speed of a forwarder on two different sites (km/h) (Visser et al., 2017)

	Site A	**Site B**
Speed while emptied	3.53	6.51
Speed while loaded	3.27	6.18

The mean speed of an unloaded forwarder is 0.25 km/h faster than when loaded on Site A, and 0.34 km/h quicker at Site B. The speed measured between the two sites showed a large difference of nearly 3 km/h. The difference could be due to factors such as the terrain on site, the model of forwarder used, or the operator's preferences. A time study conducted by Strandgard & Mitchell (2015) showed a faster average speed when loaded compared to unloaded. The loaded forwarder often has less vibrations, causing the operator being comfortable travelling at a higher speed. A time study conducted by Rutherford & McNeel (1994) during a selective harvest has the distance travelled by the forwarder both loaded and unloaded, as well as the time taken. The forwarder travelled at 2.75 km/h when loaded, and 5.83 km/h when unloaded. This demonstrates that the size of the load has a significant impact on forwarders speed.

The speed control system for on-road autonomous vehicles can be constructed using large samples of data from consumer grade GPS devices. Speed data for each vehicle type are categorised based on a number of factors such as vehicle weight, engine size and road speed restrictions (Anastassov et al., 2017).

The forwarder control system will vary from the on-road speed control system, as the tracks used in the harvest area are unfamiliar to the forwarder. Navigating new territory requires the sensor system to have high computational power as it needs to select a path, avoid obstacles, differentiate between the terrain types, choose a travel speed, and an appropriate acceleration or deceleration (Shiller and Gwo, 1991).

Terrain categories

The terrain category can be measured manually or autonomously. One way to measure the terrain manually is to measure the height of the slash-and-stumps with a measuring tape (Table 2) and to then calculate the percentage of area it covers (Howard and Seraji, 2001). Slash-and-stumps help reinforce the soil, reducing the impact of off-road machines. Operators should consider the thickness of the slash/stumps and area of ground covered before deciding to move through the forest (Berg et al., 1992). Terrain can be described using seven factors of; ground conditions, surface structure, inclination slope, surface treatment resistance, boulder quota, slash/stumps and snow (Berg et al., 1992). Each category is measured on a scale of 1-5 (Table 2). Slash-and-stumps and surface structure are the only terrain factors that would be beneficial for this data collection as the sites has little to no data of the remaining five factors.

An autonomous method of measurement is to calculate the shock-load imposed on the forwarder (Stavens, 2006). The method is less accurate due to the ability of the driver to slow down and lessen the impact of the obstacle. A third way that the terrain can be distinguished is through sensors scanning the surroundings of the forwarder (Henningsson et al., 2006). As forestry companies look to adopt autonomous machinery (Visser, 2017), sensors are likely to be developed to determine the category of terrain.

Objectives

- Measure the speed a forwarder travels over various categories of terrain while loaded and unloaded.
- Measure the deceleration of a forwarder as it
    - Approaches an obstacle
    - Comes to a stop while loaded
    - Comes to a stop while unloaded

- Measure the acceleration of a forwarder as it:
    - Passes an obstacle
    - Speeds up from a stop while loaded
    - Speeds up from a stop while unloaded

Site and Operator Description

Mayfield (20/8/2018)

The harvest crew worked for Russell Sinclair Logging on a flat 70 hectare block. The forwarder on site was a Komatsu 855 with a 14 tonne loading capacity and had been used for 14000 hours. The forwarder was operated by a 44 year old male with five months experience. The harvest area was spread out with logs stacks throughout the cutover. The amount of 'terrain under the rough track category (Table 4) was minimal as the smooth track split off into the cutover to access the log stacks. Figure 2 shows a map from the GPS data collect from the forwarder. The image is from pre harvest and fails to show any topography, terrain, or terrain boundaries.

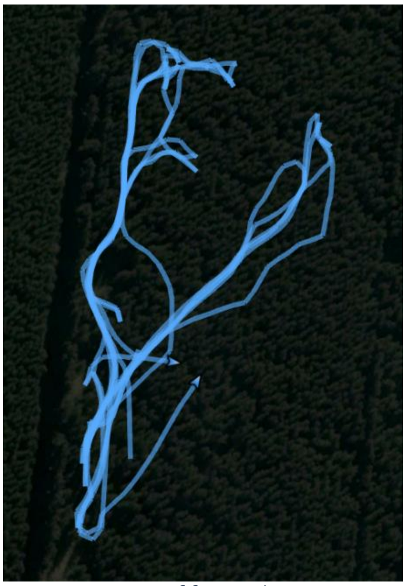

Figure 2: Map of forwarders routes at Mayfield

Stillwater (3/9/2018)

The harvest crew worked for Davies Logging at Stillwater located 10 mins outside of Greymouth. The forwarder was a new Tigercat 1075C with a 20 tonne loading capacity and 250 hours on the clock. The forwarder was operated by a 61 year old male who has six months experience. The harvest area was on flat land but had very weak top soil. There was a firm surface about 800 mm underneath the top soil. The forwarder created deep tracks filled with mud and water covering the obstacles as it travelled through the cutover. The hump in the middle of the tracks scraped the underbelly of the forwarder with an 800 mm clearance. The routes taken by the forwarder run parallel to the plantation forest rows displayed in Figure 3. Access to the harvest area was restricted due to its swamp like nature and inability to see any obstacles under the top soil.

Figure 3: Map of the forwarder routes at Stillwater

The terrain category was estimated while travelling in the cab, while no obstacles could be measured.

Balmoral Forest (5/9/2018)

The harvest crew worked for Lee Logging at Balmoral Forest in North Canterbury. The forwarder was a John Deere 1910E forwarder with a 19 tonne loading capacity and 10,000 hours on the clock. The forwarder operator was a 30 year old male with 12 years' experience. The harvest area was flat with some small slopes that lead to some river terraces. There were ruts up to 10 inches high on the landing, with the rest of the harvest area being dry with a firm topsoil. The sharp corners in Figure 4 would often act as the terrain boundary and involve the forwarder applying a three-point-turn.

Figure 4: Map of forwarder routes at Balmoral Forest

Method and Data Quality

The data collection was captured on a Garmin GPSmap 60CSx mounted onto a forwarder. The GPS was in a casing with an aerial and tied to the forwarder so it could had maximum satellite coverage with little interference. According to the FAA's (Federal Aviation Administration) website, testing of the Garmin GPS was conducted in the United States. It was found to be accurate to 1-2 meters horizontal (Garmin International Inc., 2007). The accuracy of the GPS is assumed to stay consistent at each location. The GPS was set to store its coordinates once per second. The time, date and coordinates of the GPS are recorded after each second, or less often if the forwarder is travelling at a slower speed or has stopped. If the forwarder is travelling at slower velocities, the GPS will record data less frequently and lose accuracy.

The site will be assessed during the data collection to differentiate the terrain and locate obstacles the forwarder travels over. The terrain and obstacles are categorised using the Terrain Classification System for Forestry Work (Berg et al., 1992). Slash-and-stumps can be measured using two methods; both systems use terrain classes of 1-5.

Method one involves measuring the height of the slash-and-stumps, and the percentage of area covered in slash and stumps, shown in Table 2. Slash thickness is measured with a tape measure, while the percentage of slash cover was assessed visually.

Table 2: Slash and stumps classification (Berg et al., 1992)

Class number	Slash cover (%)	Slash thickness (cm)
Class 1	10	10
Class 2	10-60	20
Class 3	60-90	30
Class 4	90-100	30<
Class 5	Terrain more difficult that Class 4	

Method two involves taking a measurement of the thickness of slash while it is being compressed under the foot. The 5 classes are calculated using the slash thicknesses in Table 3.

Table 3: Classifying slash-and-stump categories

Class	Slash thickness (cm)
1	0-2
2	3-10
3	11-20
4	21-30
5	30 <

The data collected is separated into four categories described in Table 4 overleaf.

Table 4: Terrain category descriptions

Terrain category	Description
Landing	-Slash and stumps: class 1 -Other larger obstacles (machinery and log stacks)
Smooth track	-Has been driven over at least twice previously -Slash and stumps : class 1
Rough track	-Has been driven over at least twice previously -Slash and stumps: class 2-5
Cutover	-No obvious track -Slash and stumps: class 2-5

The terrain often has a definitive boundary, prompting the operator to change speed. A mark was created on the GPS at each terrain boundary, to produce a map on Google Earth outlining different terrain categories.

A GoPro was installed to the front of the forwarder to view the obstacle that causes the forwarder to change speed. Maintaining the GoPro positioning and angle of view could have been problematic if it was struck by a branch. Monitoring the GoPro angle of view and battery life was achieved by ensuring the forwarder operator stopped at regular intervals to inspect. Data analysis involved differentiating between the forwarder being loaded and unloaded. The forwarder was classed as loaded after the forwarder had picked up its last log.

Throughout the data collection, the operator was asked to travel over specific obstacles and homogenous strips of terrain to gather some quality data, improving the outcome of the study. Access was granted to enter the cab of the forwarder at all three locations so notes could be taken during the data collection. This was also a chance to gain a small insight into how the terrain affects the operator's decisions. The data collection lasted for as long the harvest manager would allow, typically around 4-6 hours, or the duration of the baterries. Once the data collection was completed, the GoPro and GPS were dismounted and returned to the lab to extract the data.

When extracting the data from the GPS onto excel, the time, date, and coordinates extracted from the GPS are found in the same corresponding cell. Kutools (software app) was used to help separate data extracted and put it into a workable format.

To calculate the speed, acceleration, and deceleration of the forwarder, the distance and time between each coordinate was used. To find the distance between the coordinates (decimal degrees), the latitude and longitude were converted into lateral and longitudinal meters. The measurement of 111139 meters was used to convert latitude into meters lateral, while the measurement to convert the longitude into meters longitudinal continually changes. The equation to find the meters longitudinal continuously was not needed for the accuracy of the data collection. To gain an accurate change in longitudinal distance, Equation 1 was used to calculate the longitudinal multiplier. These are shown in Table 5.

(1)

$$Longitudinal\ Multiplier = \frac{\sqrt{(Distance\ on\ Google\ Earth)^2 - (\Delta Latitide * 111139)^2}}{\Delta Longitude}$$

Table 5: Constants to find the longitudinal distance between coordinates for each site

Longitudinal Multiplier	Location
81586	Alex Davies (Stillwater)
81565	Steve Lee (Balmoral Forest)
81014	Russell Sinclair (Mayfield)

Once the coordinates were converted into meters, the Pythagoras Theorem was used to calculate the distance between each coordinate given by the GPS data in excel. The speed was calculated using Equation 2:

(2)

$$Speed\left(\frac{km}{h}\right) = \frac{Change\ in\ Distance\ (km)}{Change\ in\ Time\ (h)}$$

Acceleration was measured using the unit's m/s^2. To get the acceleration, the speed was first converted to m/s by dividing the current speed (km/h) by a factor of 3.6. The acceleration was then calculated by using Equation 3 below:

(3)

$$Acceleration\left(\frac{m}{s^2}\right) = \frac{Speed_{final}\left(\frac{m}{s}\right) - Speed_{Initial}\left(\frac{m}{s}\right)}{Change\ in\ time\ (s)}$$

Analysing the data on excel can be made easier by first distinguishing between the speed, acceleration and deceleration data. The data collected didn't always show smooth accelerations or decelerations. To allow the data to be analysed, the rolling average method can be applied to the smooth the data. Rolling averages involves finding the average of three cells, including the previous, current, and next cell. The acceleration was calculated from the speed data after applying the rolling average method.

The GoPro doesn't have an internal clock so when the GoPro was first turned on and started, the time was recorded as a reference. The GoPro footage could then aligned to the timing of the GPS data. When the GPS data showed the forwarder accelerating or decelerating, the GoPro was used to view the obstacle that caused the change in speed. Some of the obstacles that were analysed from the GoPro footage include:

- Stumps
- Slash
- Other machinery

Each of the obstacles that noticeably effected the forwarders speed were measured with a tape measure and categorised into Table 6:

Table 6: Classifying obstacles by height

Obstacle category	Obstacle height (cm)
H20	10-30
H40	30-50
H60	50-70

All obstacles upto H60 can pass underneath the forwarder, however only obstacles of H20 and H40 are able to pass underneath the tyres of the forwarder.

The following list of gear was provided by the School of Forestry to undergo the data collection:

- GoPro
- GoPro spare batteries
- GoPro cover and mounting
- Garmin GPSmap CSx60
- GPS case and aerial
- Duct tape
- Zip ties
- Knife
- PPE
- Tape measure

The data collected at each site did not cover each terrain category. The acceleration and deceleration data was often interrupted or lacked consistency. Table 7 shows how many times the data collected at each site was used as part of the results section. Scenarios that only have data collected from one site is deemed statistically insignificant.

Table 7: The amount of times data was collected for each site and category

Data		**Mayfield**	**Stillwater**	**Balmoral Forest**
Number of cycles recorded		7	6	11
Speed of forwarder loaded	*Landing area*	7	6	11
	Smooth trail	7	2	11
	Rough track	0	7	8
	Cutover	5	0	4
Speed of forwarder unloaded	*Landing area*	7	6	9
	Smooth trail	7	1	8
	Rough track	2	6	8
	Cutover	4	1	2
Speed when travelling over an obstacle	*Acceleration*	0	0	6
	Deceleration	0	0	6
Deceleration to a stop	*Unloaded*	0	0	3
	Loaded	0	3	4
Acceleration from a stop	*Unloaded*	0	3	3
	Loaded	0	0	4

Results and Analysis

Speed of forwarder over each terrain category

The average speed of the forwarder on each terrain category was measured. The data was separated subject to whether the forwarder was loaded or unloaded (Figure 5).

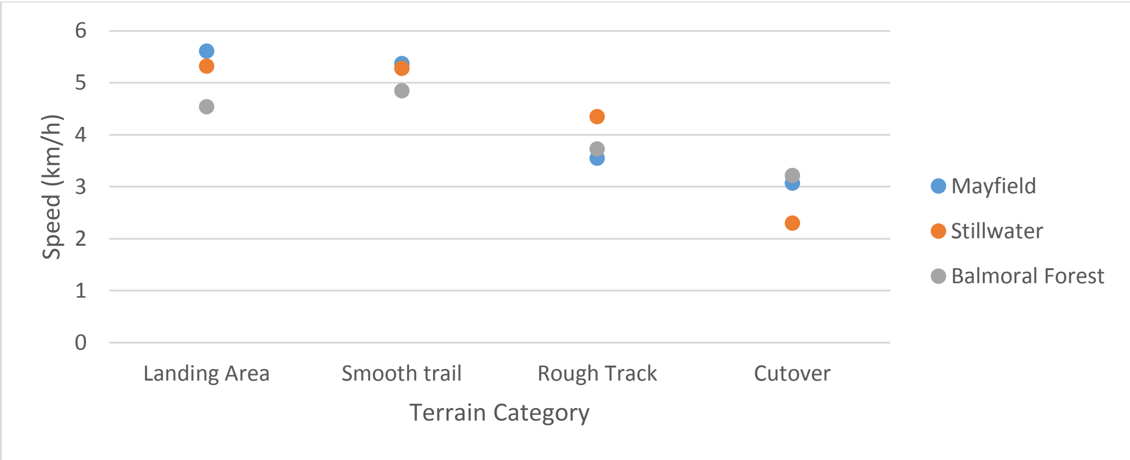

Figure 5: Speed of forwarders when unloaded

The speed of the forwarder travelling on the landing averaged the fastest speed out of the four terrain categories at 5.2 km/h (variance of 0.20). The average speed on the smooth track was 5.2 km/h (variance of 0.05). The average speed on the rough track was 1.3 km/h (variance of 0.12) slower that the smooth track, while the speed on the cutover was nearly half the speed of the smooth track at 2.9 km/h (variance of 0.16). The speed over each of the terrain categories while loaded is shown in Figure 6.

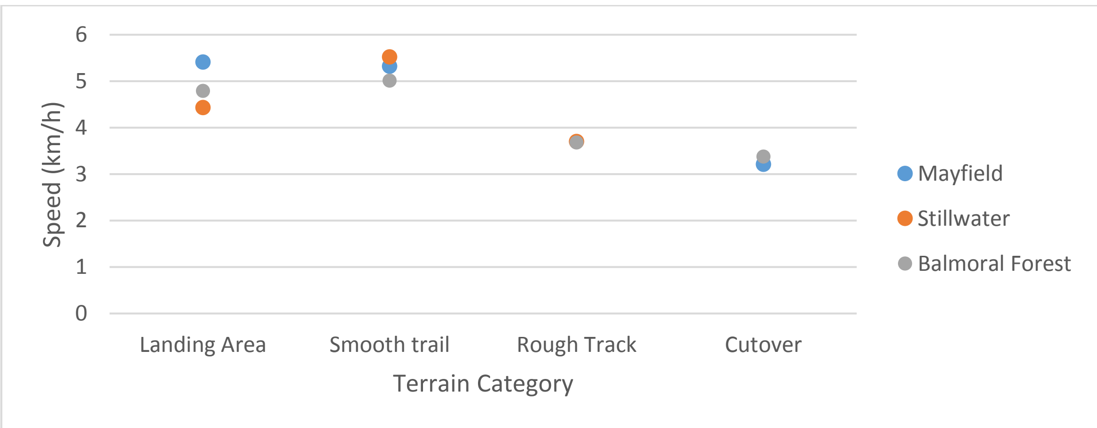

Figure 6: Speed of forwarders when loaded

The average speed of the forwarder while loaded showed a similar trend to when it was unloaded. The average speed travelling on the landing was reduced to 4.9 km/h (variance of 0.16), as well as the average speed of the rough track reducing to 3.7 km/h (variance of 0.00). Balmoral Forest and Stillwater had very similar speeds while travelling over rough tracks, while Mayfield didn't have enough data collected to be included in the category. The speed travelled on the smooth track slightly increased to 5.3 km/h (variance of 0.04) as well as the speed on the cutover by the largest difference of 0.5 km/h (variance of 0.38). Table 8 compares each of the average speeds when loaded and unloaded.

Table 8: The average speed of a forwarder when loaded vs. unloaded (km/h)

	Landing area	Smooth track	Rough track	Cutover
Unloaded	5.2	5.2	3.9	2.8
Loaded	4.9	5.3	3.7	3.3
Difference	-0.3	0.1	-0.2	0.5

The forwarder travelled 0.3 km/h faster while unloaded on the landing compared to being loaded. On the contrary, the forwarder travelled 0.5 km/h slower on the cutover while unloaded compared to loaded. The rough and smooth track showed differences of 0.2 and 0.1 km/h respectively.

Speed when travelling over an obstacle

The forwarder travelled over an obstacle six times during the data collection at Balmoral Forest. The obstacle was a stump that measured 280 mm high, and 250 mm wide falling into the category of H20. The acceleration started at different times before reaching the stump as shown by the speed graph in Figure 7. The data has been centralised so the stump is passed at the same time of 11 seconds for each cycle. The forwarder was unloaded during cycles 1 and 6, while loaded during cycles 2-5.

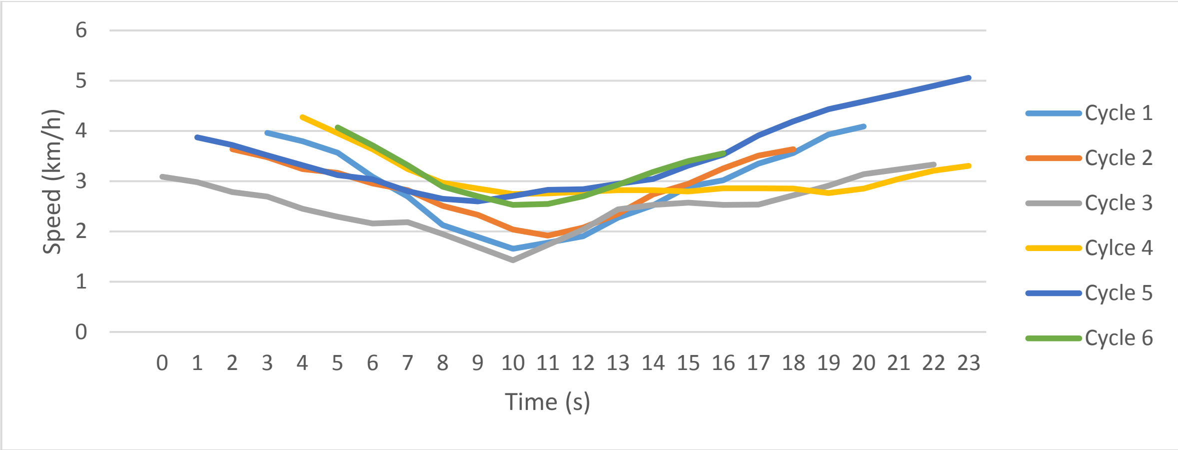

Figure 7: Speed when travelling over an obstacle of size H20 at Balmoral Forest

The lowest speed reached for each cycle lasted a short period of 1-2 seconds. The distance between the front and rear tyre of the John Deere 1910E was approximately nine meters. The average minimum speed across all cycles when travelling over the obstacle was 2.2 km/h (variance of 0.3 km/h). Assuming that the minimum speed was held while travelling over the obstacle, it would take 14 seconds to pass. Cycle 4 shown in Figure 7 had the highest minimum speed across the obstacle of approximately 2.8 km/h. The forwarder took 12 seconds to travel 9.3m, similar to the distance between the front and rear tyres, confirming that; on average it would take more than 10 seconds to pass an obstacle.

Deceleration before the obstacle has been passed

The speed profiles in Figure 9 are spread out depending on when the forwarder operator started to decelerate. If the forwarder started decelerating 6 seconds before reaching the obstacle, the average deceleration would be larger. The average deceleration for each cycle is shown in Table 9.

Table 9: Average deceleration before the stump has been passed

Acceleration *(m/s²)*		
Cycle	**Unloaded**	**Loaded**
1	0.08	
2		0.05
3		0.04
4		0.05
5		0.04
6	0.07	
Average	0.07	0.05

The average deceleration while loaded was smaller at 0.05 (m/s^2) compared to 0.07 (m/s^2) while unloaded.

Acceleration after the obstacle has been passed

Once the obstacle has been passed, the forwarder will accelerate back to an appropriate speed. The acceleration can be visualised after 11 seconds on the speed graph in Figure 7. The average acceleration for each cycle after the obstacle is shown in Table 10.

Table 10: Average acceleration after the obstacle has been passed

Acceleration *(m/s²)*		
Cycle	**Unloaded**	**Loaded**
1	0.07	
2		0.07
3		0.04
4		0.03
5		0.05
6	0.06	
Average	0.06	0.05

The forwarders average acceleration after passing the obstacle unloaded is 0.06 m/s^2. The average acceleration while loaded is slightly higher at 0.6 m/s^2. The acceleration and deceleration of the forwarder when loaded is the same at 0. 05 m/s^2, although it is slightly different when unloaded at 0.7 and 0.6 m/s^2 respectively.

Deceleration to a stop

Balmoral Forest

Figure 8 shows the speed of the forwarder as it comes to a stop on 4 different cycles. The stopping time is 11 seconds regardless of its initial speed.

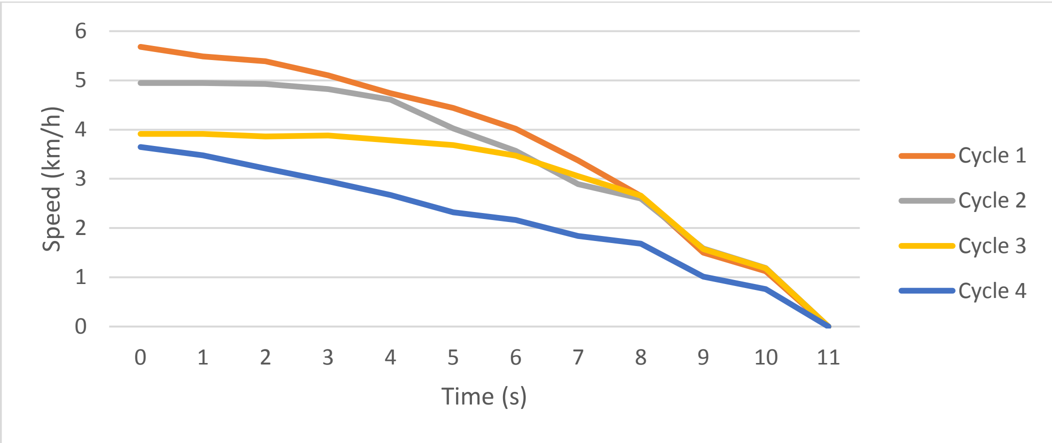

Figure 8: Speed of forwarder when decelerating to a stop while loaded at Balmoral Forest

The average deceleration of the four cycles is 0.12 m/s^2. The initial speed and rate of deceleration of the four cycles are shown in Table 11 below.

Table 11: Analysis of the forwarder decelerating while loaded at Balmoral Forest

Cycle	Initial speed (km/h)	Average Deceleration *(m/s²)*
1	5.7	0.14
2	4.9	0.13
3	3.9	0.10
4	3.6	0.09

The forwarders deceleration to a stop and the time taken to come a stop while unloaded is consistent for all three cycles shown in Figure 9.

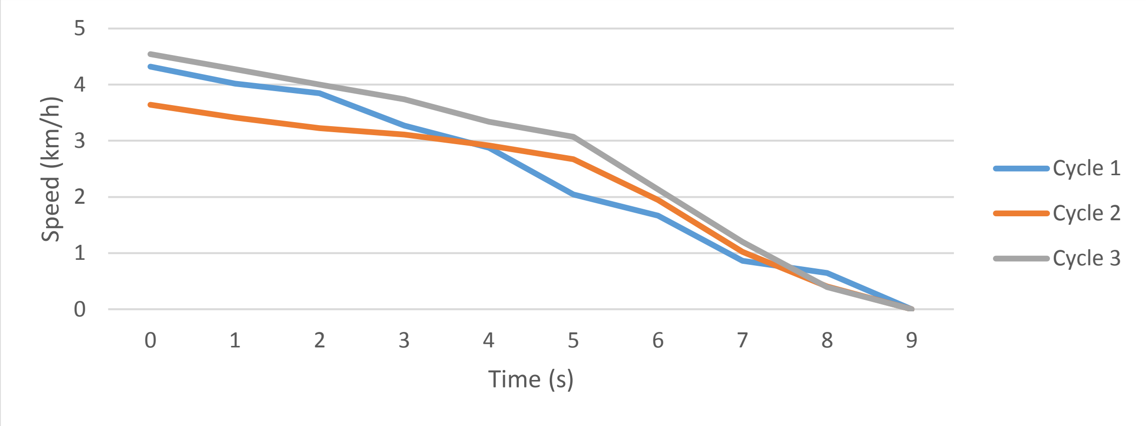

Figure 9: Speed of forwarder when decelerating to a stop unloaded at Balmoral Forest

Cycles 2 and 3 show a slight deceleration followed by a heavier deceleration after 5 seconds, while Cycle 1 shows a steady deceleration throughout the 9 second period. The average deceleration of the unloaded forwarder coming to a stop is 0.13 m/s^2, which is a larger deceleration of 0.1 m/s^2 when compared to the forwarder while loaded. The initial speed and rate of deceleration of the three cycles are shown in Table 12.

Table 12: Analysis of the forwarder decelerating while unloaded at Balmoral Forest

Cycle	**Initial speed (km/h)**	**Average Deceleration *(m/s^2)***
1	4.3	0.13
2	3.6	0.11
3	4.5	0.14

Stillwater

Figure 10 shows the forwarder coming to a stop on the landing for three separate cycles. The stopping times range from 7-12 seconds and are not directly correlated with the initial speed in this small dataset.

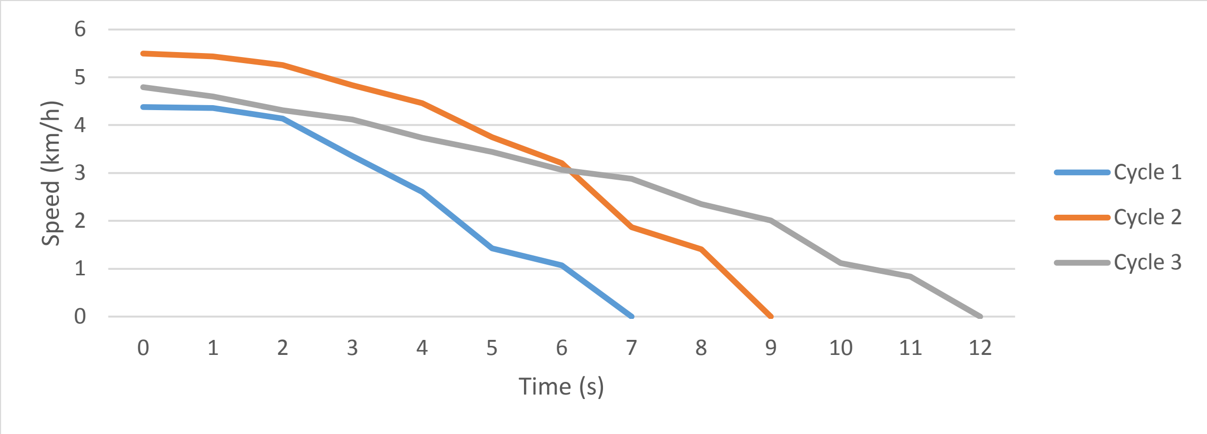

Figure 10: Speed of forwarder when decelerating to a stop while loaded at Stillwater

The average deceleration while loaded is 0.17 m/s^2. Cycle 3 takes 12 seconds to decelerate from 4.8 km/h resulting in a smaller deceleration of 0.11 m/s^2. The deceleration of the forwarder while loaded is higher than the deceleration of the forwarder at Balmoral Forest by 0.05 m/s^2. Cycle 3 however shows a similar deceleration to Balmoral Forest averaging 0.11 m/s^2. The initial speed and average rate of deceleration of the three cycles are shown in Table 13.

Table 13: Analysis of the forwarder decelerating while loaded at Stillwater

Cycle	Initial speed (km/h)	Average deceleration *(m/s^2)*
1	4.4	0.17
2	5.5	0.17
3	4.8	0.11

Acceleration from a stop

Balmoral Forest

The acceleration data in Figure 11 was collected at the start of the forwarders cycle while unloaded on the landing with no obstacles impeding its path.

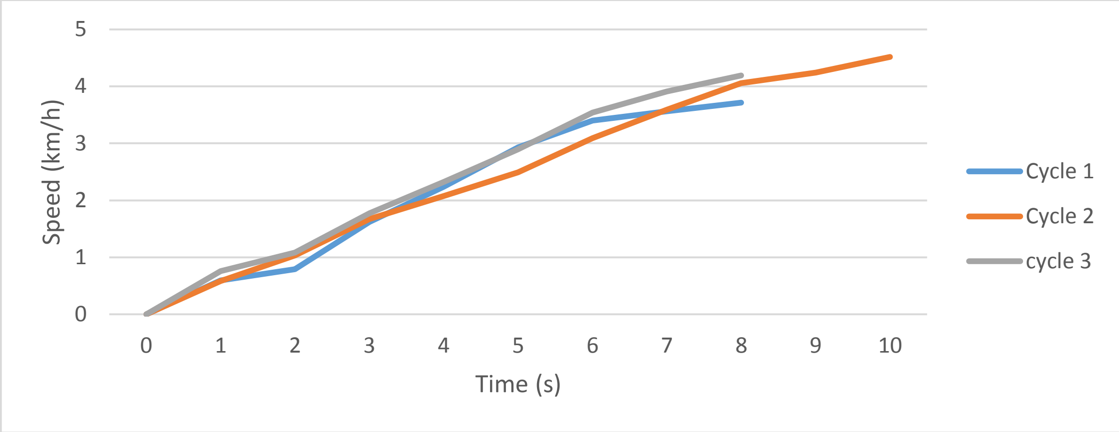

Figure 11: Speed of forwarder when accelerating from a stop unloaded at Balmoral Forest

Accelerating from a stop while unloaded shows a linear increase in speed that is constant between each of the three cycles in Figure 11. The average acceleration of the three cycles is 0.13 m/s^2, with the initial speed and average rate of acceleration of the three cycles are shown in Table 14.

Table 14: Analysis of the forwarder accelerating while unloaded at Balmoral Forest

Cycle	Final speed (km/h)	Average acceleration (m/s^2)
1	3.7	0.13
2	4.5	0.13
3	4.2	0.15

Acceleration of the forwarder from a stop while loaded is shown for four cycles when at Balmoral Forest (Figure 12).

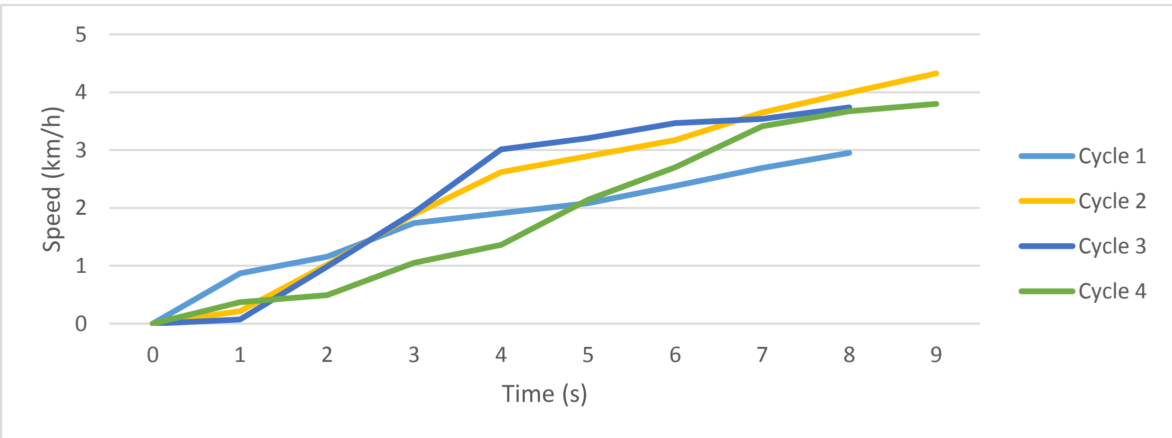

Figure 12: Speed of forwarder accelerating from a stop while loaded at Balmoral Forest

The average acceleration from a stop while loaded is 0.12 m/s^2 which is slightly lower when compared to the average acceleration of the forwarder unloaded. The final speed and average rate of acceleration for each of the four cycles are found in Table 15.

Table 15: Analysis of the forwarder accelerating while loaded at Balmoral Forest

Cycle	Final speed (km/h)	Average acceleration *(m/s^2)*
1	3.0	0.10
2	4.3	0.13
3	3.7	0.13
4	3.8	0.12

Stillwater

Figure 13 shows the speed graph of the forwarder accelerating from a stop three times. The average acceleration for each cycle is very similar, regardless of its final speed.

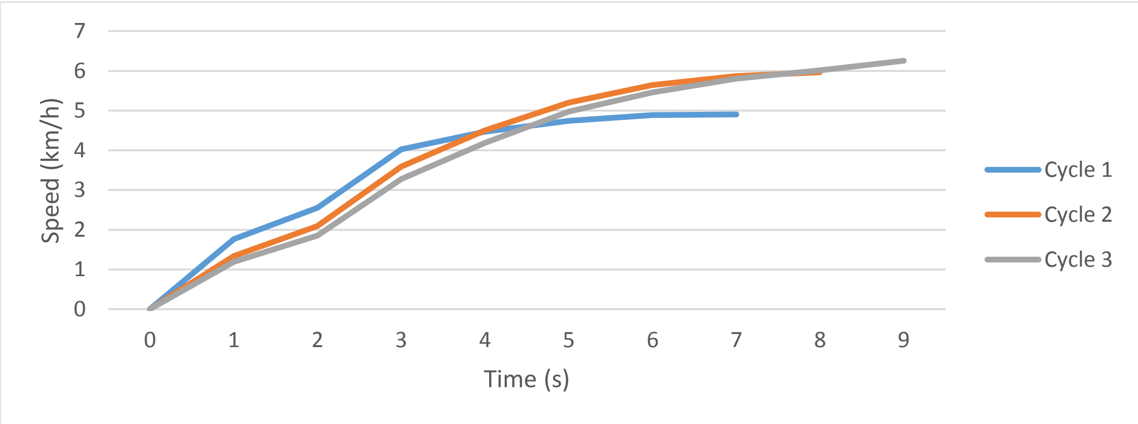

Figure 12: Speed of forwarder when accelerating from a stop unloaded at Stillwater

The average acceleration for each of the three cycles is very similar regardless of the final speed at 0.2 m/s^2. This is relatively large acceleration when compared to Balmoral Forest and is potentially due to the operators preferred style of driving. The final speed and average rate of acceleration of each of the 3 cycles is shown in Table 16.

Table 16: Analysis of the forwarder accelerating while unloaded at Stillwater

Cycle	Final speed (km/h)	Average acceleration *(m/s^2)*
1	4.9	0.19
2	5.9	0.21
3	6.2	0.19

The speed recommendations in Table 17 have been made by analysing the data collected during this study. The recommended speeds have been averaged using data from all three sites which showed consistent results for each terrain category.

Table 17: The recommended speed for each scenario

Scenario	Speed (km/h)
Speed on landing while loaded	4.9
Speed on landing while unloaded	5.2
Speed on a smooth track while loaded	5.3
Speed on a smooth track while unloaded	5.2
Speed on a rough track while loaded	3.7
Speed on a rough track while unloaded	3.9
Speed on the cutover while loaded	3.3
Speed on the cutover while unloaded	2.9
Speed to decelerate to when passing over an H20 obstacle	2.1

The recommended rates of acceleration and deceleration have been averaged using data collected from Balmoral Forest. The small amount of acceleration and deceleration data collected from Stillwater had higher values than Balmoral Forest. The average rates of acceleration and deceleration can be found in Table 18 and 19 respectively.

Table 18: The recommended acceleration for each scenario

Scenario	Acceleration (m/s^2)
Acceleration when advancing from a stop while loaded	0.12
Acceleration when advancing from a stop while unloaded	0.13
Acceleration when advancing from an obstacle while loaded	0.05
Acceleration when advancing from an obstacle while unloaded	0.06

Table 19: The recommended deceleration for each scenario

Scenario	Deceleration (m/s^2)
Deceleration when coming to a stop while loaded	0.12
Deceleration when coming to a stop while unloaded	0.13
Deceleration when coming to an obstacle while loaded	0.05
Deceleration when coming to an obstacle unloaded	0.07

Conclusion

The results revealed little to no difference between the speeds travelled on the landing and smooth track categories, or whether the forwarder was travelling loaded vs. unloaded. The forwarders speed decreased when travelling on the rough track and further decreased when travelling on the cutover, showing a direct correlation between the forwarders speed and the category of slash-and-stump.

The average deceleration was 0.12 m/s^2 when coming to a complete stop, compared to 0.6 m/s^2 when decelerating for an obstacle on the forwarders path. The difference between the decelerations is likely due to the relative decrease in velocity that is required for each scenario. The rate of acceleration and deceleration was approximately 0.1 m/s^2 higher when the forwarder was unloaded compared to loaded. The smaller rate of deceleration when loaded could be due to the braking ability of the forwarder not being as efficient when compared to unloaded. The smaller rate of acceleration while loaded could be due to the forwarder needing more power to accelerate due to the added weight of the load.

Limitations of the study include visiting three sites, yet only having one site return enough quality acceleration and deceleration data to make inferences. The GPS accuracy is assumed to be consistent throughout each site from which data was collected. If given additional time to conduct a more thorough study, it would allow for further data to be collected and analysed, giving more reliable results.

The results of this study can be used as an indication of expected speed data when building a speed control system for an autonomous forwarder. Harvest areas are made up of a range of scenarios that a forwarder comes across, only some of which were analysed during this study. Suggestions for future research could involve an analysis of the forwarder travelling over differently sized obstacles, driving on slopes, and looking at the maximum deceleration in the case of an emergency.

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