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Effect of Trail Condition, Slope, and Direction of Extraction on Forwarding Performance: Insights from a Controlled Comparative Study

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Abstract: The performance of timber harvesting equipment is important for local operational planning and for making decisions on the way in which the forests should be opened up. However, there are many options used to extract timber, and there is a high variability in their performance. Forwarding is commonly used and became an attractive option for low-access forests. A controlled experiment was set up in this study to see how the configuration of the trails, characterized in terms of slope and surface condition, and the extraction direction (uphill or downhill) may affect the performance of forwarding operations. GNSS (Global Navigation Satellite System) data were collected at a rate of 5 s for five replications of moving empty downhill and uphill, respectively, on a dirt trail, measuring 250 m in length and having a slope of about 11%. The same experiment was run with the machine loaded at full capacity, then four replications with the machine loaded and unloaded moving downhill and uphill, respectively, were performed on a forest road resembling a rocky trail, which measured 390 in length and had a slope of about 4%. GNSS data were used to extract the moving speed for all the tested conditions with the aim to compute the cycle time, and the payload volume estimate was used to estimate efficiency, and productivity, depending on extraction distance in a range of 50 to 1000 m. For the first trail, statistical comparison tests indicated significant differences in the speed of uphill and downhill movement, for both empty and loaded conditions, whereas for the second trail, there were no significant differences in speed. In addition, on the second trail, the sustained speed was almost double. These were reflected sharply in the cycle time, efficiency, and productivity, depending on extraction distance and trail condition. These findings are important for decision making on local operational planning and forest opening up.

Keywords: forwarding; trail condition; extraction direction; extraction distance; performance

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1. Introduction

The performance of timber harvesting systems has become essential in sustaining the competitiveness of the forest sector, not only in finding the best solution for a localized harvesting problem [1,2] but also in making other informed decisions, such as the way in which the forest roads are planned and developed [3–5].

Forwarding is a common method used around the world [6–8], mainly due to benefits it brings to a society that values and tries to balance the economic, ecological, and social effectiveness. For instance, forwarding with specialized machines enables the extraction of high payloads per turn, which increases the productivity and lowers the fuel use [9–11]; such payloads are typically composed of cleaner logs, which helps in minimizing the rejection rate at the factory gate [12], whereas modern forwarders provide a certain degree of flexibility in technology and components [13].

However, as with any machine operating off-road, the performance of forwarders is affected by factors such as trail condition and direction of extraction. Trail condition is typically evaluated in terms of moisture and slope, to which the type of soil or material present at the surface may be added. In mountainous areas, for instance, there is a wide variability in trail slope and surface type, which can be the soil or the bedrock. A forwarder trail should be ideally opened as straight line and with a low slope to enable an efficient extraction. A forest road network serves truck transportation, and its degree of development is another important factor that may affect the performance of harvesting operations, which, in turn, is important in planning it right, e.g., [3,14]. A forest road network with a higher density will limit the extraction distance and improve the economic and environmental performance of forwarding operations by mechanisms such as a higher productivity and a lower unit fuel use [11]. Nevertheless, there is a high variability in national forest road densities, from about 7 to 55 m/ha [15], which requires a performance analysis to make the right decisions. The way in which the forest road network is developed also affects the extraction direction. In regions that have forest roads developed alongside the main valleys, the extraction is commonly conducted downhill, whereas in those regions having a denser forest road network, typically developed on the slopes, the extraction can be conducted uphill and downhill, respectively.

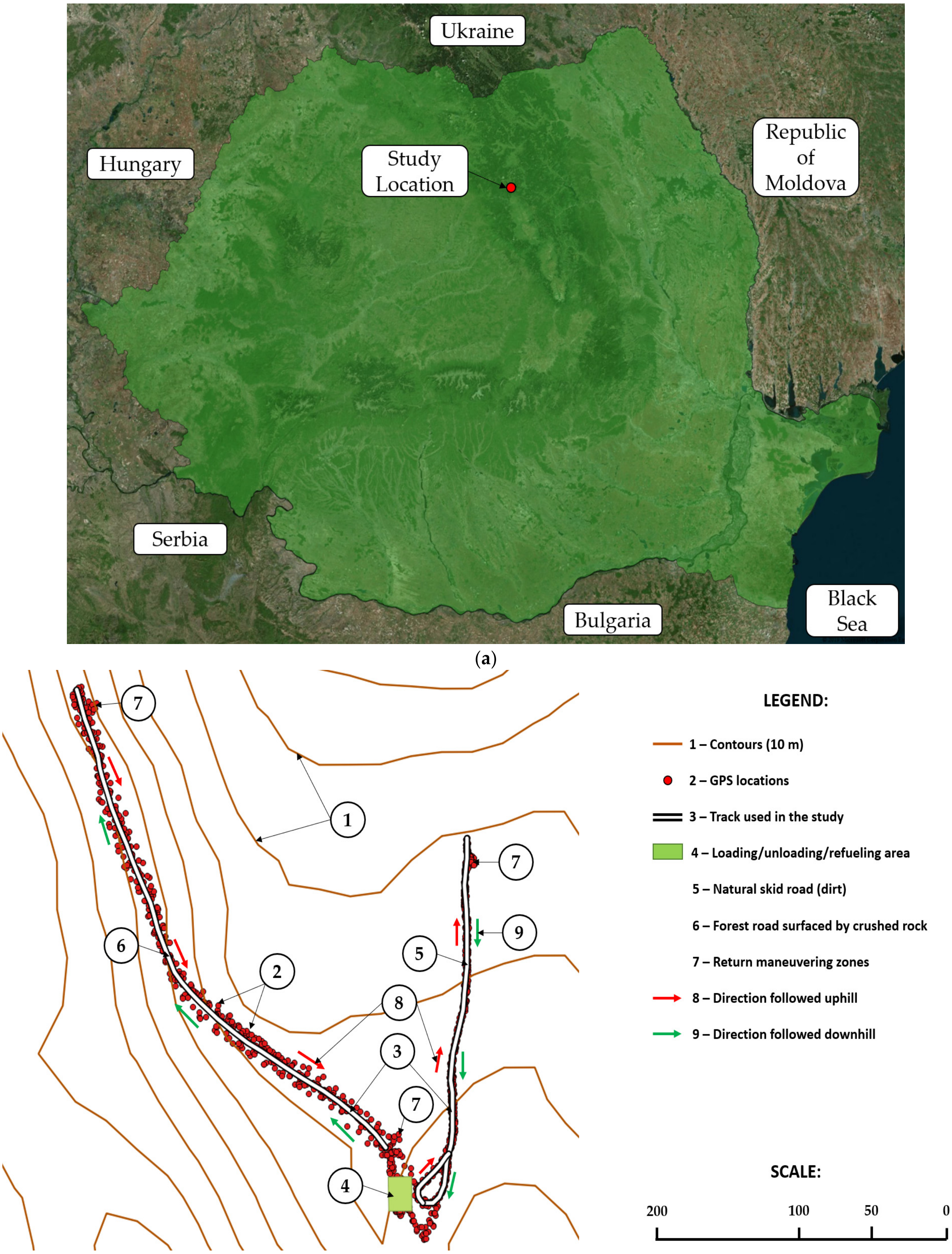
While forwarding performance has been extensively studied in flat-terrain forest areas, there are only couple of studies on the performance of forwarding in sloped terrain, e.g., [16–18], and, despite the availability of observational studies indicating differences between downhill and uphill forwarding [19], no studies are available to evaluate the productive performance by controlled experiments to see how the condition of the trail and direction of extraction may affect it. In turn, such information is essential for the local planning of operations, for the attempts to update or develop the forest road network, and for the general forest science.

The goal of this study was to evaluate the performance of forwarding by considering the trail condition and extraction direction, where the performance was measured in terms of speed, cycle time, efficiency, and productivity. The first objective of the study was to check whether there are significant differences in operational speed caused by the trail condition in terms of slope and surface type, state of machine during the operation (loaded or unloaded), and direction of movement (uphill and downhill), as a prerequisite to fulfill the second objective of the study. The second objective of the study was to estimate the differences in cycle time, efficiency, and productivity as a function of extraction distance, so as to have a clear picture on how the trail condition affects the operational performance.

2. Materials and Methods

2.1. Study Area and Machine Description

The area of study was selected near the city of Topliţa, Harghita county, Romania (Figure 1). Mountain forests from the area are characterized by an important share of Norway spruce (*Picea abies* (Lam.) Link.), and, as typical to Romania, the stands are frequently located at high distances from the forest road network, which is a factor that significantly lowers the productivity. In Romania, timber extraction by specialized forwarders is typically carried out by private wood harvesting contractors. A local contractor owning a HSM 208 F series forwarder agreed to support the study. Typically, the contractor fells and processes the tress motor-manually, and the logs are extracted by forwarding. The forwarder features an engine power of 185 kW, a weight of 18 t, a payload capacity of 14 t, and a hydrostatic transmission that enables a speed between 0 and 14 km/h in the first gear. The machine was equipped with an Epsilon M70 F80 (Palfinger, Elsbethen-Glasenbach, Austria) crane with a range of 8 m.



(**a**)

(**b**)

Figure 1. Location of the study and layout of the selected trails: (**a**) location of the study at the national level; (**b**) layout of the selected trails. Note: maps developed in QGis (https://www.qgis.org/, accessed on 5 June 2019) based on the field collected GNSS data and open-source layers.

In the Romanian conditions, when working in sloped terrains, to keep the machine in a good range of trafficability and to prevent excessive erosion, the literature recommends planning the trails and skid roads with low longitudinal slopes, typically accounting for 5 to 15%. Accordingly, two locations were selected to plan the trails required by the study (Figures 1 and 2). The first one was planned on an undisturbed soil, had a length of 250 m and a mean longitudinal slope of 11%, being located near a forest in an open pasture (Figure 2a). This trail was selected to resemble similar ground conditions when working in forests by driving directly on the soil, and it was called hereafter the "dirt" trail. The second trail (Figure 2b) resembles the conditions of operation in high-altitude forests where there is likely to be a mix of soil and rock at the surface. To meet these conditions, a portion of a degraded forest road was selected for the second trail, showing a mixture of soil and rock at the surface, having a length of 390 m, and a mean longitudinal slope of about 4%; this trail is called hereafter the "stone" trail. As a rule, both trails were selected to show some wetness during the experiment, a condition which is typical to most mountain operations. To exercise a higher degree of control over the experiment aiming to detect the changes in operational speed caused by the empty and loaded, and the uphill and downhill movement, respectively, the trails were selected so as to have no sideway obstruction by trees. In addition, the trails were as straight as possible, avoiding this way the effects on speed that could be brought about by curved portions.

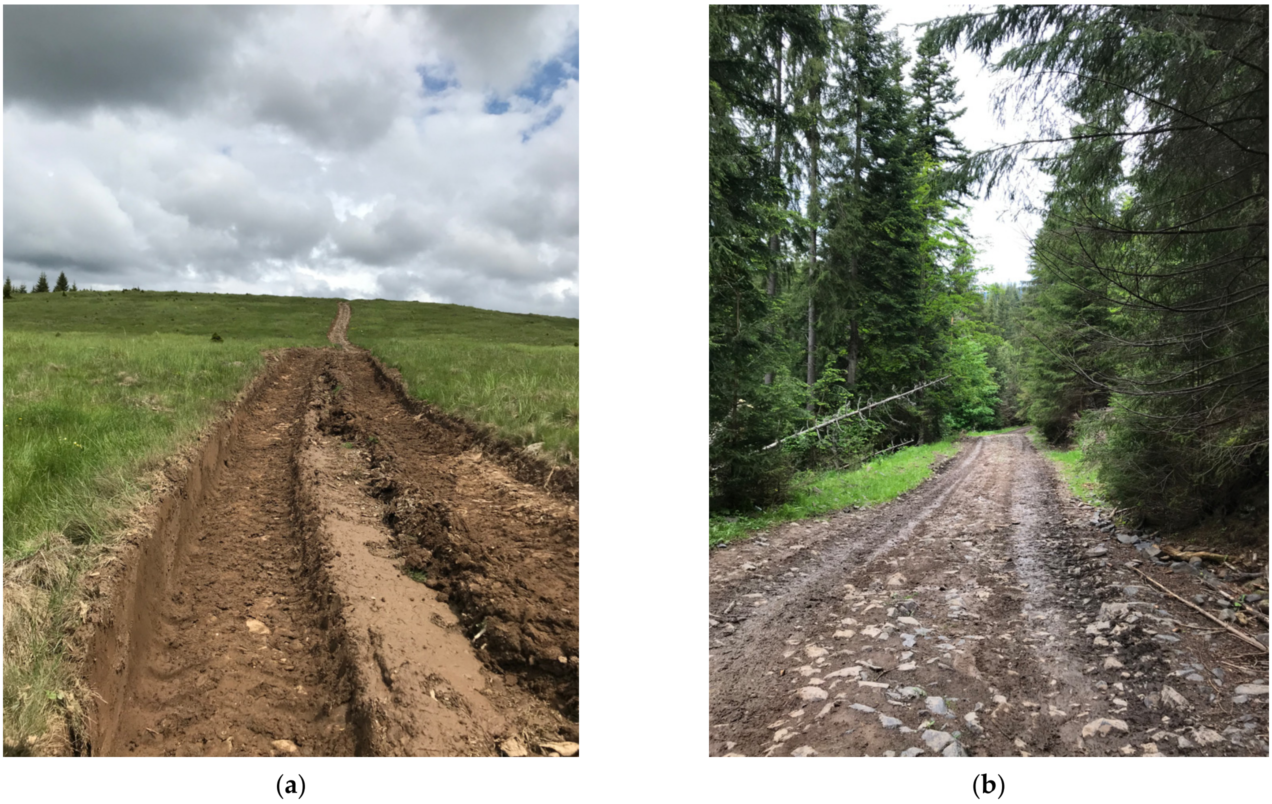

(**a**) (**b**)

Figure 2. Trails selected for the study: (**a**) dirt trail appearance at the end of the experiment; (**b**) stone trail appearance at the end of experiment.

Once the trails were selected, an area was established at their joining point for loading–unloading experiments (Figure 1b), which were run with a pile of logs brought to the site in advance. Of these, a set of logs that fulfilled the conditions of forming a full-capacity payload were selected and measured in detail in advance of the experiment with the aim of taking their biometric features, such as length and large and small end diameters. These measurements were carried out on a number of 24 Norway spruce logs featuring a diameter at the small end of 26.29 ± 13.57 cm (range of 9 to 60 cm), a diameter at the large end of

36.25 ± 13.99 cm (range of 19 to 68 cm), and a length of 6.24 ± 0.49 m (range of 5.1 to 6.6 m), which are log dimensions commonly practiced in the area when using motor–manual tree felling and processing. Log volume estimates were based on the Smalian's formula, resulting in an estimated payload size of 14.03 m^3. Since the wood was fresh, the estimated payload was about 10 tons, adding to the mass of the forwarder during the loaded turns, which was of 18 tons.

2.2. Experimental Design and Data Collection

To run the experiment, the most important events considered were those of driving uphill and downhill with the empty and loaded bunk, respectively, on both trails. However, these also required maneuvering at the end of the trails, as well as stopping to fuel the machine, and to run loading and unloading events. The driver, who had about five years of experience on the machine taken into study, was instructed on how the experiment should be carried out, and he had to follow a sequence of events consisting of driving uphill and downhill with the empty bunk for couple of times on the same trail, followed by driving in the same sequence with the loaded bunk. This sequence was repeated 5 times on the dirt trail and 4 times on the stone trail. The reason for repeating only 4 times on the stone trail was that of obtaining relatively balanced datasets since it was assumed that a higher speed could be sustained on the stone trail, given its lower slope and higher bearing capacity. In short, the protocol begun with maneuvering, to place the machine near the wood pile location, loading the machine, driving uphill and downhill five times with the bunk loaded on the dirt trail, in which all these events were intercalated with maneuvering at the ends of the trail, then driving uphill and downhill with the bunk loaded on the stone trail four times, which included the maneuvering at the ends of this trail, six loading and unloading repetitions performed at the log storage area, and driving unloaded uphill and downhill five and four times on the dirt and stone trail, respectively. Table 1 describes the events, driving direction, bunk state, trail conditions, and abbreviations used when making comparisons for the same trail, between trails and when simulating the performance based on the data collected during the experiment.

Table 1. Description of the factors and abbreviations used for experimental design.

Operation	Event	Driving Direction	Bunk State	Trail Condition	Abbreviations Used for Comparison for the Same Trail	Abbreviations Used for Comparison between Trails	Abbreviations Used for Simulation of Performance
-	Stopped	-	-	Dirt	S	S	-
-	Maneuvering	-	Empty	Dirt	ME	ME_D	-
-	Driving	Uphill	Empty	Dirt	DUE	DUE_D	-
-	Driving	Downhill	Empty	Dirt	DDE	DDE_D	-
-	Maneuvering	-	Loaded	Dirt	ML	ML_D	-
-	Driving	Uphill	Loaded	Dirt	DUL	DUL_D	-
-	Driving	Downhill	Loaded	Dirt	DDL	DDL_D	-
-	Stopped	-	-	Stone	S	S	-
-	Maneuvering	-	Empty	Stone	ME	ME_S	-
-	Driving	Uphill	Empty	Stone	DUE	DUE_S	-
-	Driving	Downhill	Empty	Stone	DDE	DDE_S	-
-	Maneuvering	-	Loaded	Stone	ML	ML_S	-
-	Driving	Uphill	Loaded	Stone	DUL	DUL_S	-
-	Driving	Downhill	Loaded	Stone	DDL	DDL_S	-
Forwarding	-	Uphill	-	Dirt	-	-	UF_D
Forwarding	-	Downhill	-	Dirt	-	-	DF_D
Forwarding	-	Uphill	-	Stone	-	-	UF_S
Forwarding	-	Downhill	-	Stone	-	-	DF_S

Note: S—stopped, irrespective of the location, ME—moving empty, DUE—driving empty uphill, DDE—driving empty downhill, ML—maneuvering loaded, DUL—driving loaded uphill, DDL—driving loaded downhill, _D—dirt trail experiment, _S—stone trail experiment, UF—forwarding uphill, DF—forwarding downhill. Please note that the events were combined to characterize the forwarding as a typical operation.

The speed that can be sustained during the events of driving the machine depends on several factors, such as the geometry of the trail, ground condition of the trail, slope, and the eventual obstacles that occur sideways of the trail. Often these factors limit the safety and comfort of the driver during the operation of the machine; therefore, the drivers prefer to adapt the speed of driving based on their own experience and on how they feel the interaction between the machine and the ground. Therefore, the driving speed can be different for the same trail conditions between different drivers, and it is preferred to have drivers with a high experience in similar operations to obtain conclusive results. However, the ability to sustain higher speeds is important for both fuel saving and increasing the productivity [9]. To have a reference on how to run the experiment, after explaining the protocol to be followed to the driver, he was asked to operate the machine at a speed at which he felt completely comfortable and safe inside the cab.

As an important data source, operational speed during all the events and repetitions was monitored at a rate of five seconds by a Garmin GPS Map series (GPSMAP 64 STC, Garmin, Romania) handheld data logger, which was placed on the forwarder's cab. Tracking machines in forest operations by GPS became a widely accepted practice, including in the attempt to procure data for time studies, e.g., [20,21]. This is because GNSS (Global Navigation Satellite System) technology is currently providing accurate location data [22], and it can accurately document the speed of movement [23,24]. At the end of the experiment, the data were saved as .GPX files and then were exported as Excel files via Garmin BaseCamp ® (Version 4.7.0). Then, the data were analyzed based on the location of the trails and geometry of the collected locations and coded based on the events and states described in Table 1.

The event-based data were then used for simulations concerning the estimated cycle time (for which the measurements taken in the field were converted into hours), efficiency, and productivity, as a function of extraction distance. To cover both the international and national conditions in terms of access to the stands, the extraction distance considered was between 50 and 1000 m. For simulation, a work cycle was defined according to Equation (1) by considering the typical organization of work in forwarding operations, e.g., [16–19].

$$\mathrm{FWC_{ij}} = \mathrm{ET_{ij}} + \mathrm{DL} + \mathrm{LT_{ij}} + \mathrm{UP}, \tag{1}$$

where FWC stands for a forwarding work cycle, ET stands for the empty turn, DL stands for driving between log bunches and loading, LT stands for the loaded turn, UP stands for unloading and piling, i stands for the trail type (i = either dirt or stone), and j stands for the direction of extraction (j = either downhill or uphill).

In other words, the simulation of cycle time, efficiency, and productivity considered the trail type and extraction direction as the main conditions. Driving between log bunches and loading was estimated based on the log characteristics used in the experiment, typical degree of log concentration following the type of felling and processing method used, and the extraction intensity in the area. This resulted in an estimate of 0.167 h for DL. The unloading and piling (UP) time was estimated from the field experiment based on six repetitions of unloading, which averaged 48 s (0.013 h). The empty (ET) and loaded turn (LT) times were estimated based on the median operational speeds (see Section 2.3) collected from the field for the trail (i) and extraction direction (j) by assuming that forwarding uphill will involve empty turns carried out downhill and vice versa. Efficiency and productivity were estimated based on the general concepts described in [25] by considering the estimated forwarding cycle time and the payload size. For each extraction distance from 50 to 1000 m, trail condition, and direction of forwarding, cycle time (hours), efficiency, and productivity were computed, assuming a step of 50 m in extraction distance. This approach was helpful to plot and analyze the variation in these three operational parameters as a function of trail condition and extraction direction.

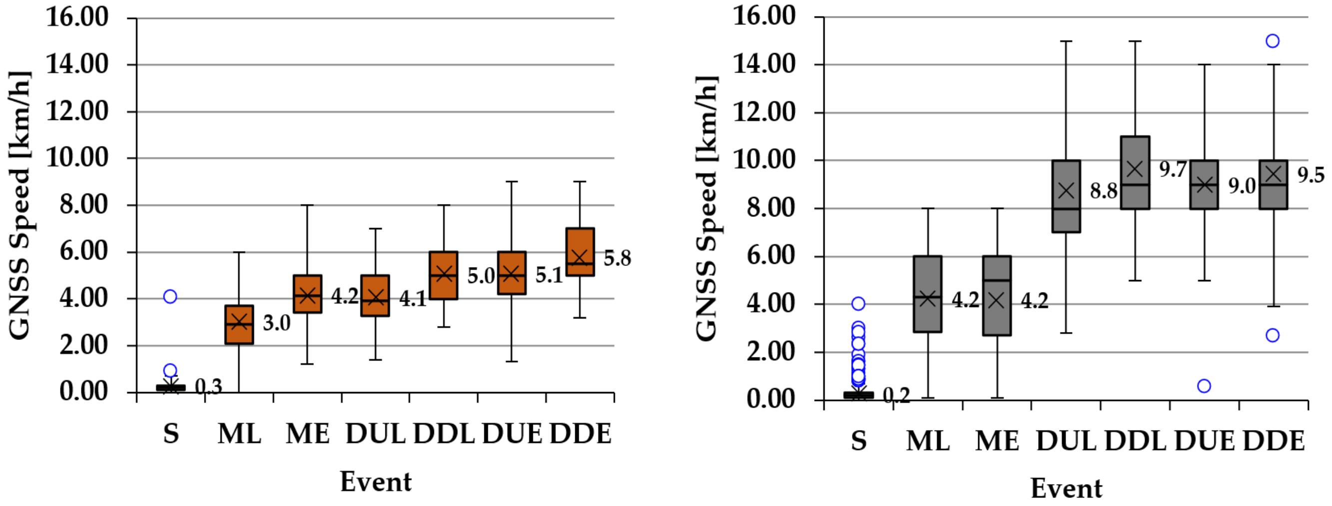
2.3. Statistical Analysis

Statistical analysis concerned mainly the comparison between the operational speed of events for the same trail and between the operational speed of the same event occurring on different trails. For the same trail, comparisons were carried out between maneuvering empty and loaded, and driving uphill and downhill empty and loaded, respectively. These comparisons were conducted to check whether there were statistically different speeds caused by the bunk state for the same driving direction. To emphasize the effects brought about by the trail condition, a given event in terms of driving direction and bunk condition from the dirt trail was compared against its correspondent from the stone trail. Statistical analysis was supported by the use of Real Statistics add in [26], which is a free tool that extends the statistical capabilities of Microsoft Excel (version 2016). To choose the right statistical comparison test, a normality check over the speed data was conducted using the Shapiro–Wilk test [27]. Given the outcomes of the test, according to which the normality held true only for some maneuvering data, a non-parametric Mann–Whitney test [28] for two independent variables was used for comparison, and the outcomes of the test were compared in terms of probability and effect size. Since there was a high likelihood to have duplicates in the speed data (several datapoints in the datasets having the same value), the test was implemented with a correction for ties and hypothesis testing was based on the figures of Mann–Whitney's exact test. The test works with continuous variables among the compared groups, such as speed data from this study. It can accommodate non-normal data, with similar shapes of the data distributions, and requires randomly selected independent samples of sufficient size that can contain different numbers of observations [29]. All of these assumptions were met by the design of the study.

3. Results

3.1. Effects on Operational Speed

Figure 3 summarizes the descriptive statistics of operational speed based on the event, driving direction and bunk state. In favorable operating conditions, GNSS speed represents a fair, although underestimated, figure of the real movement speed [23,24], while the GPS devices are already providing a good accuracy [22].



(**a**) (**b**)

Figure 3. Descriptive statistics of the operational speed datasets: (**a**) data for dirt trail; (**b**) data for stone trail. Legend: S—stopped, ML—maneuvering loaded at the end of the trail, ME—maneuvering empty at the end of the trail, DUL—driving uphill loaded, DDL—driving downhill loaded, DUE—driving uphill empty, DDE—driving downhill empty.

Overall, the dirt trail provided poorer conditions to sustain higher speeds as compared to the stone trail. Maneuvering, for instance, was conducted at a much smaller speed when the machine was loaded on the dirt trail, which could be an effect of the trail condition and slope. Besides a consistently higher speed sustained during maneuvering at the ends of the stone trail, it appears that there were low differences in the data distribution caused by the bunk state (Figure 3). The most important differences caused by the direction of driving and bunk state appeared to be those characterizing the dirt trail datasets. By the conditions of the experiment, driving uphill loaded could be sustained at a median speed of 4.1 km/h, which was the lowest in the driving events. Driving uphill empty was conducted with an addition of one unit in the speed, while driving downhill loaded was carried out at a slower speed compared to empty driving. While for the dirt trail, there were obvious differences in the operational speed of these events, on the stone trail, the differences were not as obvious as expected. Maneuvering with an empty and loaded bunk, respectively, were performed at the same average speed, although the median speed was higher when maneuvering empty. Driving uphill loaded and empty, respectively, returned close average values, accounting for about 9 km/h, which were almost double compared to the same events on the dirt trail. In terms of both median and average values, there were no evident differences when driving downhill loaded and empty on the stone trail (Figure 3b).

Figure 4 shows a comparison of relevant events, driving directions, and bunk states in a paired approach that considers the trail condition. As a general rule, the operational speeds were much lower on the dirt trail, and the magnitude of difference was high, with almost double values for the same event, driving direction, and bunk state on the stone trail.

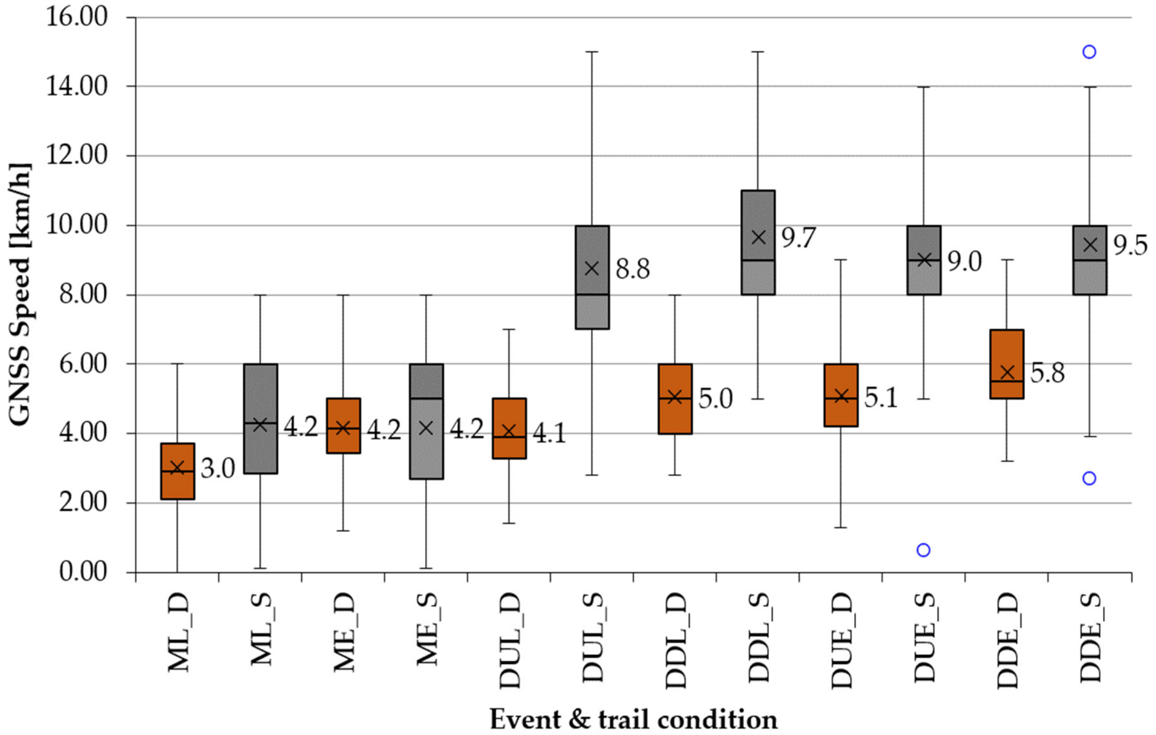


Figure 4. A comparison of descriptive statistics of the events by considering the trail condition. Legend: ML_D—maneuvering loaded at the end of the dirt trail, ML_S—maneuvering loaded at the end of the stone trail, ME_D—maneuvering empty at the end of the dirt trail, ME_S—maneuvering empty at the end of the stone trail, DUL_D—driving uphill loaded on the dirt trail, DUL_S—driving uphill loaded on the stone trail, DDL_D—driving downhill loaded on the dirt trail, DDL_S—driving downhill loaded on the stone trail, DUE_D—driving uphill empty on the dirt trail, DUE_S—driving uphill empty on the stone trail, DDE_D—driving downhill empty on the dirt trail, DDE_S—driving downhill empty on the stone trail.

Another finding was that there were small differences in the speed sustained for loaded or unloaded, downhill and uphill driving when operating on the stone trail, which was not the case of the dirt trail. As a consequence, there were statistically significant differences ($p < 0.001$, $\alpha = 0.05$) and medium to strong effects (r = 0.261 to 0.417) between the speed of maneuvering, driving uphill, and downhill events when the bunk state was considered for the dirt trail, which was not the case of the stone trail (Table 2). Except for maneuvering while the bunk was empty (Table 3), there were statistically significant differences ($p < 0.001$, $\alpha = 0.05$) and medium to very strong effects (r = 0.339 to 0.806) brought by the trail condition for the same event, driving direction, and bunk state.

Table 2. Event-, driving direction-, and bunk state-based comparison results for each trail.

Condition of the Trail	Compared Events [1]	Effect r	*p*-Value
D	ML-ME	0.354	<0.001
D	DUL-DUE	0.417	<0.001
D	DDL-DDE	0.261	<0.001
S	ML-ME	0.014	0.888
S	DUL-DUE	0.078	0.234
S	DDL-DDE	0.014	0.832

[1] Excepting ME (for dirt trail) and ML (for stone trail), all the variables failed the normality test.

Table 3. Comparison results of operational speed due to the condition of the trail.

Compared Events [1]	Effect r	*p*-Value
ML_D-ML_S	0.339	<0.001
ME_D-ME_S	0.063	0.549
DUL_D-DUL_S	0.806	<0.001
DDL_D-DDL_S	0.799	<0.001
DUE_D-DUE_S	0.781	<0.001
DDE_D-DDE_S	0.722	<0.001

[1] Excepting ME_D and ML_S, all the variables failed the normality test.

These come as an obvious outcome when looking at the median speeds sustained on the stone trail, as seen in Figure 4, which ultimately may be caused by the lower slope of the trail and the better bearing capacity it had at the time of experiment.

3.2. Effects on Cycle Time, Efficiency, and Productivity

Although the speed sustained in one of the objective indicators of a system performance [30], for the science and practice of forest operations, cycle time, efficiency, and productivity comparisons make more sense [31], since these figures can be readily integrated into cost figures or optimization models. Figures 5–7 show the variation in cycle time, efficiency, and productivity of forwarding by considering forwarding direction (downhill or uphill) and trail condition (dirt or stone). Irrespective of the case, cycle time increased as a function of the extraction distance, which is a common behavior in transportation processes. For very low extraction distances (50 m, Figure 5), the differences in cycle time were low, but as the extraction distance increased, the cycle time increased at a higher magnitude for dirt trail. For this trail condition, cycle time seems to have only minor differences for a distance range of 50 to 250 m when considering the downhill versus uphill forwarding, but as the extraction distance increases, so do the differences in cycle time, indicating a more efficient condition for downhill forwarding. This was not the case of the stone trail, where the variation in cycle time was similar for uphill and downhill forwarding. This was a consequence of similar operational speeds in the events composing the work cycle. At 500 m, the stone trail was characterized by cycle times lower by 0.087 to 0.107 h compared to the dirt trail. The magnitude in cycle time differences between the two increased at 0.175 to 0.213 h when considering a distance of 1000 m.

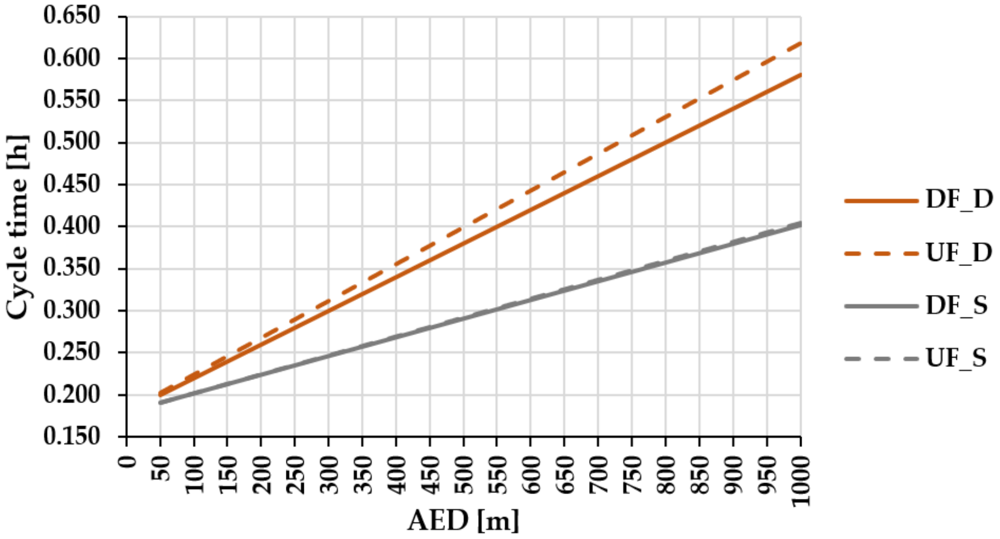


Figure 5. Variation in cycle time as a function of average extraction distance (AED) when considering the direction of forwarding and trail condition. Legend: AED—average extraction distance, DF_D—downhill forwarding on the dirt trail, UF_D—uphill forwarding on the dirt trail, DF_S—downhill forwarding on the stone trail, UF_S—uphill forwarding on the stone trail.

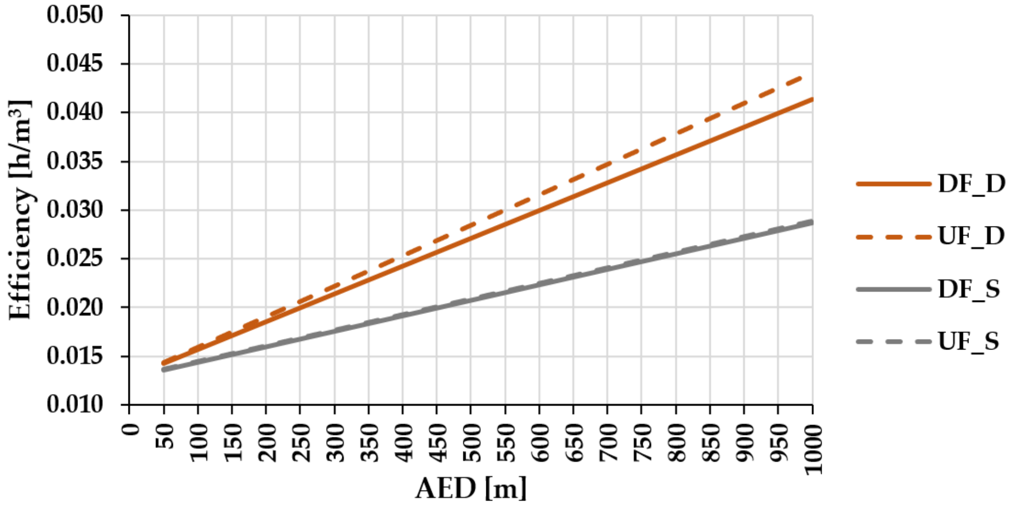


Figure 6. Variation in efficiency as a function of average extraction distance (AED) when considering the direction of forwarding and trail condition. Legend: AED—average extraction distance, DF_D—downhill forwarding on the dirt trail, UF_D—uphill forwarding on the dirt trail, DF_S—downhill forwarding on the stone trail, UF_S—uphill forwarding on the stone trail.

These differences were reflected in efficiency (Figure 6) and productivity (Figure 7), since the payload size was kept constant in the simulation. A decreasing trend in efficiency as a function of extraction distance was observed, with a higher changing rate for the dirt compared to the stone trail, and with important differences for the dirt trail when the direction of extraction was taken into account.

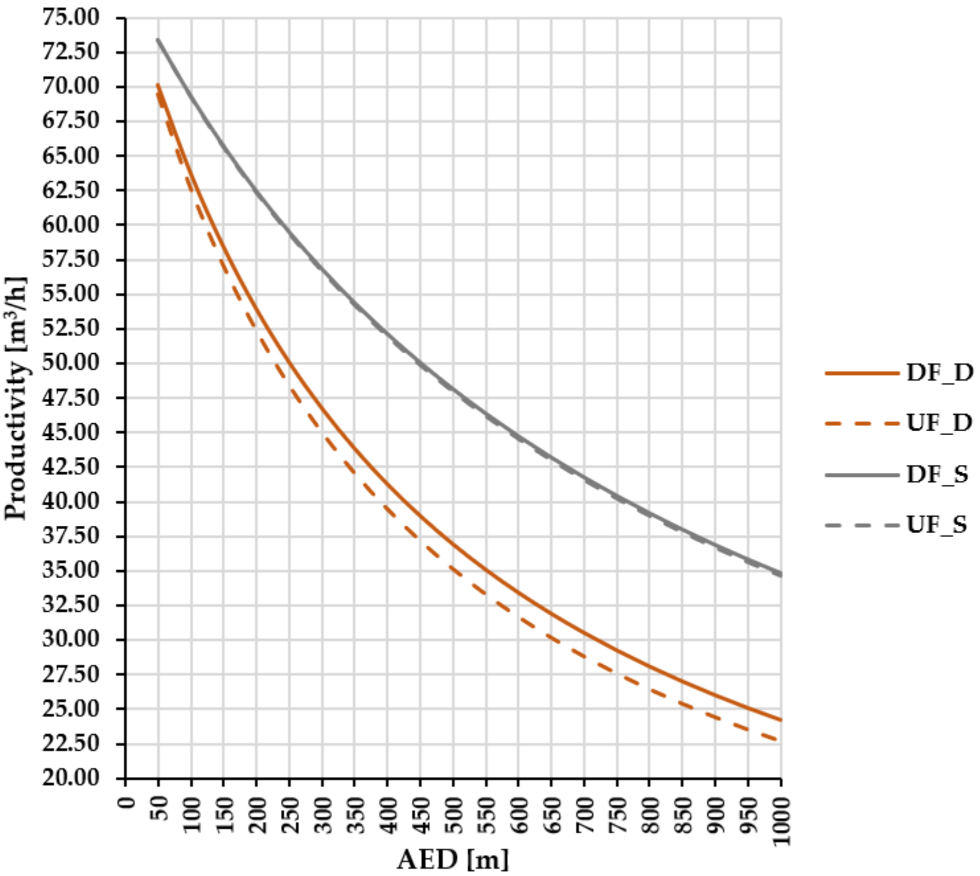


Figure 7. Variation in productivity as a function of average extraction distance (AED) when considering the direction of forwarding and trail condition. Legend: AED—average extraction distance, DF_D—downhill forwarding on the dirt trail, UF_D—uphill forwarding on the dirt trail, DF_S—downhill forwarding on the stone trail, UF_S—uphill forwarding on the stone trail.

For the considered conditions, the estimated productivity was very high for short distances (50 m, Figure 7), but it decreased sharply as the extraction distance increased, being only half at an extraction distance of 1000 m for the stone trail, and about one third for the dirt trail. No evident differentiations were found for the stone trail when considering the uphill versus downhill forwarding, which was not the case of the dirt trail. The findings are similar to those of cycle time and efficiency, in the way that for the same extraction distances, the differences in productivity were low when comparing downhill with uphill forwarding for the dirt trail. However, a higher moving speed on the stone trail improved productivity compared to the dirt trail. Starting with a difference of about 3 m^3/h for a distance of 50 m, the productivity decreased on the dirt trail at a rate that produced a difference of about 12 m^3/h at a distance of 500 m, and a difference of about 11 m^3/h for a distance of 1000 m.

4. Discussion

Performance of forwarding operations depends on many factors, including the machine size, its technical characteristics, terrain and stand characteristics, and other operational conditions, such as the extraction distance [32,33]. Driving speed, which affects the cycle time, efficiency, and productivity, is highly dependent on the ground conditions [33] and geometry of the trails [9]. However, with the existing studies, it was difficult to emphasize how trail condition may affect the driving performance in terms of speed because most of the work published so far had an observational character. It is common sense to think that uphill forwarding would be less performant than downhill forwarding, which was one of the central points of this research. Some have already indicated a decline in productivity for uphill forwarding [19], which was the case of dirt trail in this study. However, this cannot be seen as a general assumption since, on trails with lower slope and good ground conditions, the speed that can be sustained during uphill and downhill driving is similar. Indeed, the speed documented by this study may not accurately reflect the real operational speed that one can achieve on trails located in forest. This is because trails developed in the forest show frequent obstructions and obstacles, and the drivers may feel uncomfortable to drive at high speed when standing trees, for instance, are located nearby. However, quantifying the differences brought by the trail condition in under-canopy conditions may be quite difficult since controlling the experimental environment is challenging. For instance, it would be difficult to control the payload size from one turn to another; in addition, there are low spaces to turn the machine, or, by doing so, it would cause extensive damage to the soil, and there will be less space to store the logs between the trails. Therefore, the speeds found by this study are less credible for a typical operation, particularly when the stands are dense, although similar machines were found to sustain the same speed in real operational environments [9]. Taking as a reference the study of [9], for instance, for a relatively straight trail having a similar technical profile with that of the stone trail of this study, but with a wider range of longitudinal slopes, the average speed sustained was of about 7.5 to 8.0 km/h during downhill loaded and uphill empty driving, respectively. On the other hand, the speeds found by this study are credible in terms of effects brought in performance by the condition of the trail since, in the absence of any obstacles and having straight trails, the driver operated the machine close to its capacity for those conditions.

With this study, it was not possible to differentiate the effects in performance brought by the slope and those brought by the ground condition, whereas the variation in slope may act as an important factor to differentiate the speed. Accounting for the effects of both factors taken independently would have required extensive logistics and permits to identify trails in both classes of ground condition and several slope categories. Then, for each trail and slope condition, the same payload should have been used, meaning that it should have been transported at each place of testing. Another point which should be considered is the gear used for locomotion. In this study, the wheels were not equipped with tracks. Equipping the wheels with tracks will likely affect the driving speed, probably enabling higher speeds on trails which are similar to the dirt trail from this study and, as such, improvements in efficiency and productivity.

By seeing the operations in the field during the experiment, we believe that the differences in performance, as found by this study, are driven by the condition of the trail, since there was a small difference in slope between the trails. For instance, at the beginning of the experiment, the surface of dirt trail was naturally leveled and easy to drive. As the loaded and empty turns progressed, ruts were formed, so the driver probably had many more difficulties in maintaining a constant speed and a good traction during driving. In contrast, the stone trail had no important changes at the surface during or following the experiment; therefore, it provided a better driving experience, which enabled a constant speed. The stone trail from this study was a degraded forest road showing a surface condition similar to that of trails located at high altitude. Although it cannot reflect the subgrade and surface conditions of a forest road due to degradation, our results on speed recorded on this trail are consistent with those of previous research, pointing out that forest roads typically provide the conditions to drive at higher speeds [33]. In addition, as the machines and probably the driving skills are improved, it seems that the driving speed is also currently becoming higher in forwarding operations [34].

Since the results of this study are based on GNSS speed, it is worth mentioning the benefits and limitations of using this parameter to obtain operational performance estimates. GPS speed has been found to be a good estimate of the real moving speed [24]. In terms of location, under forest canopy, one may expect an accuracy of 5 to 12 m [22]. However, the accuracy is largely affected by errors brought by other factors [23], out of which large obstacles and satellite network configuration are important. This was the case of the stone trail, for which one of the sides was bordered by a rocky cliff; therefore, the accuracy of data could have been affected. In contrast, the dirt trail was under clear sky, providing better conditions for measurement; therefore, the data supporting its experiment may be more accurate. GPS was found to underestimate the real movement speed [23] and to overestimate the distance between locations [35], being further sensitive to errors during acceleration and deceleration [23]. Therefore, the real speed could have been higher compared to that from our statistics, while the acceleration and deceleration events were limited to short distances at the end of the trails when the machine accelerated to enter the trail or slowed down to take the maneuvers at the end of the trail.

Bearing in mind the results on speed, efficiency, and productivity, downhill forwarding would be a better choice when the trails meet the conditions of the dirt trail from this study, and when the extraction distance is high. For lower extraction distances, the productivity estimates were similar, showing only minor differences that could be easily balanced, for example, by slight modifications in the payload size. Concerning the stone trail, the performance was much better, but, still, areas showing this type of surface on the trails and a similar slope, is limited at least in Romania, and probably coupled with natural forests composed of smaller trees. In such conditions, the effect brought about by loading and unloading smaller and likely more logs could attenuate the positive effects brought by the driving speed.

Future studies should try to differentiate the effects of the slope of the trails on performance, giving priority to a design able to cover the variability in ground conditions. Assuming that this attempt would be logistically feasible, it would further clarify sensitivity of performance to these factors, which is important for operational planning and will provide useful information on how to further develop the forest road network. For the Romanian forests, where the skidding technology is still dominating the operations [6], planning the forest road network considered the performance of these machines against that of sledge cable yarders. Adding this new knowledge on the performance of forwarding will likely reveal new opportunities for operational planning and support better decision making, with a finer adaptation to the terrain and stand conditions. Such attempts would have to rely on more in-depth analysis of factors located in the upstream and downstream processes.

5. Conclusions

Trail condition is a factor that significantly affects the performance of forwarding, which is the main finding of this study, based on a controlled experiment. Trails exhibiting a good bearing capacity provide better driving conditions, which are reflected in increased operational speeds. There are differences in performance due to extraction direction, but these are significant only on commonly known trails that show regular soil at the surface. When the bearing capacity is high, the speeds that can be sustained during various forwarding elements are similar, meaning that there will be less differences in forwarding performance due to the extraction direction. Future studies should check in more depth the effects brought about by the slope on forwarding performance, an attempt which will bring useful data for operational planning and strategic development of the forest road network.

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