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Operational Speed in Skidding Operations by Cable Skidders and Farm Tractors: Results of a Nationwide Assessment

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Abstract

Accurate estimates of operational speed are crucial for modeling skidding productivity and planning efficient timber extraction. This study provides an event-level characterization of operational speeds in timber skidding operations in Romania, comparing cable skidders and farm tractors. Unlike most previous studies, which are based on limited datasets, this research uses a large, diverse dataset obtained through GNSS tracking over 98 field days at 14 sites, supplemented by synchronized video recordings. A total of 1.74 million seconds of data were collected, with 1.20 million seconds retained for analysis after data quality filtering. Descriptive statistics and Mann–Whitney U tests revealed significant differences in speed. For cable skidders, median speeds ranged from 1.6 km/h during maneuvering at the pre-skidding site to 5.0 km/h during unloaded driving to the pre-skidding site. For farm tractors, median speeds ranged from 2.2 km/h during maneuvering on the forest road to 6.0 km/h when driving unloaded to the pre-skidding site. The highest speeds were observed during unloaded driving, while the lowest occurred during maneuvering. Surprisingly, farm tractors outperformed cable skidders in some operational events due to more favorable terrain. The findings document GNSS-derived speed as a sufficiently reliable proxy for machine performance assessment and provide robust data for predictive modeling, operational planning, and equipment selection in forestry.

Keywords: operational speed; GNSS tracking; forestry operations; time studies; skidding performance; event-level analysis

Academic Editor: Paolo Renna

Received: 28 July 2025

Revised: 1 September 2025

Accepted: 6 September 2025

Published: 10 September 2025

Citation: Zurita Vintimilla, M.C.; Borz, S.A. Operational Speed in Skidding Operations by Cable Skidders and Farm Tractors: Results of a Nationwide Assessment. *Appl. Sci.* **2025**, *15*, 9921. https://doi.org/10.3390/app15189921

1. Introduction

Timber harvesting planning is a multi-faceted activity conducted at several decision-making levels and requires knowledge of economics, environmental impact, and social suitability [1], in addition to traditional forest science knowledge [2,3]. For instance, economics is a crucial key performance area in forest operations, typically based on efficiency and productivity assessments [4,5], which rely on time-and-motion studies [6,7].

In skidding operations, time-and-motion studies are often conducted to develop time consumption and productivity models, which generally serve as the backbone of operational planning. These models relate the resources required, such as time, to key operational factors like extraction distance and payload size. They provide tools to predict the performance of machines under various operating conditions, thereby supporting planning efforts and the management of operations in terms of time and financial resources [2,7].

Such studies have commonly been employed to assess skidding performance using specialized machines [8–12] and farm tractors equipped for forest operations [13–18], and time-and-motion methods have been used for various purposes, such as modeling and developing predictive models, e.g., [8–10,13–18], comparing the performance when using different machines or when working operational conditions [12], evaluating the environmental performance of operations [11], and simulating performance based on collected data and developed statistics [18].

As a fact, skidding is a common technical option in forest operations worldwide [19–21]. In Romania, for instance, skidding using specialized machines such as cable skidders and farm tractors designed for this purpose is the predominant method. Based on personal communications, the state forests currently maintain a fleet of 309 cable skidders and 201 farm tractors for forest operations, while private contractors operate a fleet of over 2700 skidders and more than 1900 farm tractors. The latest operational performance rates for these machines date back to the 90s [22] and are now considered obsolete, as newer models have been developed and introduced into operations. Furthermore, the country presents diverse operational conditions in terms of applied silvicultural systems, topography, accessibility, and operational time frames [2], rendering the existing models unsuitable for the new machines.

Developing time consumption models for a new and diverse fleet is challenging when performed conventionally, due to the resources required [7], which in turn restricts the size of the datasets collected and reduces the predictive power of the resulting models. This challenge arises mainly because such models need to account for a variety of factors that characterize the diversity of operations, including ground conditions, types of silvicultural systems, extraction intensity, operational seasons, and the experience of work crews, to name just a few. An alternative approach to documenting operational performance while considering a large and diverse dataset is benchmarking operational speed. To this end, several studies have utilized GNSS devices to record factors such as speed and operational distances [23–28], making this approach appropriate for monitoring operations, including detailed, elemental time-and-motion analyses.

The goal of this study was to characterize the elemental-level operational speed based on a large, diverse, nationwide dataset of operations produced through GNSS and video monitoring techniques, which serves as a proxy for developing dedicated models for commonly used machines, such as specialized cable skidders and farm tractors fitted for skidding. Several objectives were set for this study, as follows: (i) to collect diverse and detailed GNSS and video data as input for (ii) annotation of events and statistical analysis of GNSS speed at an elemental level, in order to (iii) produce robust descriptive statistics for operational speed as a proxy for model development. This study contributes to the field of operational performance in forest operations by presenting a comprehensive, nationwide dataset of operational speeds for cable skidders and farm tractors, collected through a combination of GNSS tracking and synchronized video monitoring. Unlike previous studies that relied on small, localized datasets, our approach covers a wide range of operational conditions across 14 different sites in Romania. This large-scale, event-level data collection provides a robust basis for developing further predictive models, making it a significant advancement over past studies, which often lacked the statistical power and operational diversity. Additionally, by integrating GNSS technology with real-time event annotation through video, this study offers a more precise and scalable method for assessing machine performance in forestry operations.

The structure of this paper is organized as follows: Section 1 introduces the background and objectives of the study, providing context and the rationale for the research. Section 2 describes the materials and methods used for data collection and analysis, including the GNSS tracking system, video monitoring techniques, and statistical approach, Section 3 presents the results, with detailed descriptive statistics and statistical comparisons of operational speeds for both cable skidders and farm tractors, Section 4 includes the discussion of the findings, comparing them with previous studies and addressing the challenges encountered during the research and, finally, Section 5 summarizes the main contributions of this study, and suggests future research directions related to operational speed and performance.

2. Materials and Methods

2.1. Data Sourcing

This study is based on an extensive dataset developed using GNSS-collected data from 14 study sites distributed across Romania. A study site is defined herein as a location where data was collected over one to several days of observation of skidding operations, sharing similar conditions regarding felling type, tree size and species, skid trail, and the machinery used for operations. Figure 1 shows the study sites at the national level, while Table 1 provides a description of these sites, local conditions, and types of machines used. Field data collection was conducted in 98 days between 2020 and 2022 (84 days for cable skidders and 14 days for farm tractors equipped for skidding), aiming to capture the variability induced by local conditions, crew experience, and seasonal factors. The areas of study were initially selected from a longer list of available operations and their temporal constraints. At the outset, a list of the forest directorates conducting these operations was created, and an initial selection of operations was made at random based on the availability of field data collection resources. Subsequently, as field data collection progressed and the availability and completeness of the remaining operations were assessed, the list of study locations was gradually updated using a randomized approach.

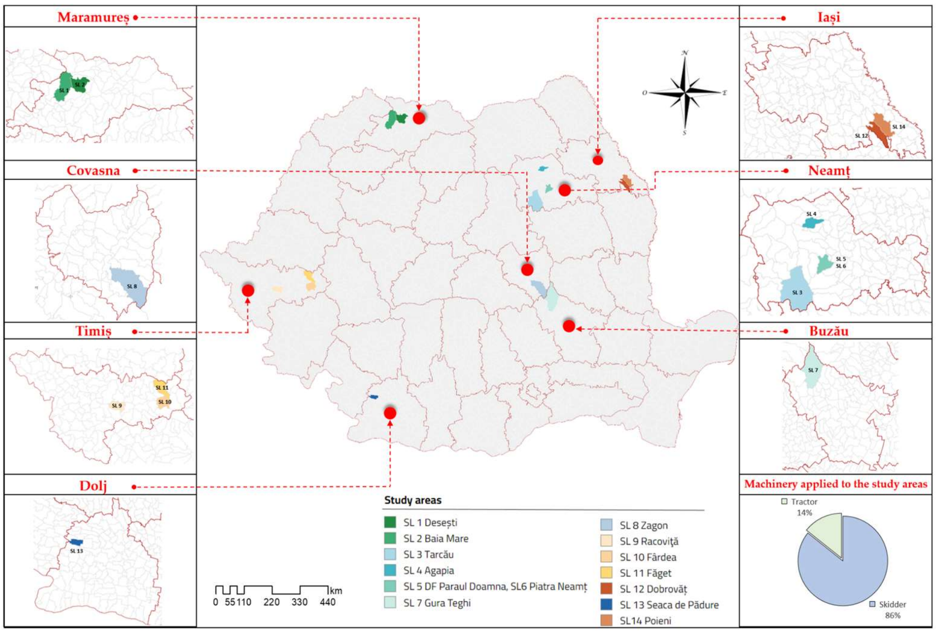

Figure 1. Map of the country showing the study areas. Legend: red dots show the counties of data acquisition, and SL1 to SL14 indicate the specific sites, each highlighted in different colors. Note: 14% of the study sites covered farm tractor-based operations and 86% covered cable skidding operations, resembling to a large extent the typical use of machines in the Romanian skidding operations.

Table 1. Summary of the field collected data, and the temporal frame of data collection.

Study Site	Type of Forest	Season	Machine Type	Skid Trail Slope	Collection Dates
S 1	Mixed	Winter	Skidder	Moderate	10 November 2020–13 November 2020
S 2	Mixed	Autumn	Skidder	Flat	21 September 2021–23 September 2021
S 3	Coniferous	Winter	Skidder	Moderate	22 November 2021–25 November 2021
S 4	Mixed	Winter	Skidder	Steep	24 November 2021–26 November 2021
S 5	Mixed	Winter	Skidder	Moderate	22 November 2021
S 6	Mixed	Winter	Skidder	Steep	23 November 2021–26 November 2021
S 7	Mixed	Spring	Skidder	Moderate	15 March 2022–24 March 2022, 3 May 2022
S 8	Mixed	Spring	Skidder	Moderate	15 March 2022–25 March 2022, 3 May 2022–6 May 2022
S 9	Broadleaved	Summer	Skidder	Flat	1 August 2022–5 August 2022
S 10	Broadleaved	Summer	Skidder	Flat	19 July 2022–29 July 2022
S 11	Broadleaved	Summer	Skidder	Steep	18 July 2022–29 July 2022
S 12	Broadleaved	Summer	Skidder	Moderate	16 August 2022–26 June 2022
S 13	Broadleaved	Autumn	Farm tractor	Flat	27 September 2021–30 September 2021, 1 October 2021
S 14	Broadleaved	Summer	Farm tractor	Moderate	16 August 2022–24 August 2022

Note: Silvicultural systems include thinning and selective extractions, applied to various tree sizes, stand densities, ages, and species, which were not purposefully quantified by the study. The dominant harvesting method was the tree length method as observed in the field. Trail condition included situations such as dry, moist, frozen, muddy, and covered by snow, whereas the trail slope was assessed visually from video data, where flat stands for up to 10%, moderate stands for about 10 to 25%, and steep stands for more than 25%.

Experimental data were collected using a protocol aimed at pairing GNSS locations with the operational events captured in the video files. For each machine observed at a given study location, a Garmin GPS Map 64s (version 4.7.5., Garmin Ltd., Olathe, KS, USA) GNSS handheld receiver was mounted on the cab to minimize potential signal interference from the machine's components. At the back of the machine, a GOPRO HERO12, produced by GOPRO Inc. (San Mateo, CA, USA), action camera was positioned and connected to an external power source to extend its recording capabilities to a full operational day.

The GNSS receiver was configured to record location data at intervals ranging from 1 to 5 s. It was equipped with replaceable batteries, providing power for more than a full day of observation. For the model used, the collected data were time-labeled and stored internally until connected to a computer for downloading. The video camera was configured to capture high-resolution footage continuously. The files were saved to the device's internal memory and, at the end of each observation day, transferred to an external hard drive together with the corresponding GNSS data. A folder structure was established to organize the data according to the study site name and day of observation, with the corresponding files copied into their respective folders.

Field observations covered two types of machines: cable skidders and farm tractors equipped for cable skidding. Cable skidders can navigate rough terrain and overcome obstacles while operating with logs of various lengths and diameters. These machines are specially designed for forest operations, and there is a large domestic manufacturer in the country that provides most of the models in use. In contrast, farm tractors are versatile machines primarily used for agricultural activities, but they can be adapted for forestry tasks such as dragging and transporting logs, particularly in small-scale operations or on less demanding terrain. In Romania, agricultural tractors equipped for skidding operations are common, especially among small-scale harvesting companies.

2.2. Data Processing

Video and GNSS data were synchronized to ensure accuracy in data alignment. This synchronization was based on observing the behavior of GNSS records processed in Garmin BaseCamp (Garmin International Inc., Olathe, KS, USA) alongside the events shown in the video files. To ensure proper synchronization between GNSS data and video observations, both datasets were plotted simultaneously in a two-dimensional line chart in Excel, with one line representing speed variation and the other representing the coded video events. In cases where the timing did not initially match, the video coding column was systematically shifted relative to the GNSS data until a clear correspondence was observed in the graph. Specifically, periods of increasing speed matched well with events such as driving to the pre-skidding site or driving with the payload to the forest road, while low or near-zero speed values coincided with stationary or low-mobility events such as load attachment, pulling in the payload, and payload detachment. This iterative adjustment process, guided by the visual overlap of the two data series in the chart, allowed us to achieve consistent alignment across all data and ensured that the synchronization was both accurate and replicable.

Daily recordings of the operations were summarized, lasting between approximately 1.5 to 8 h per day of observation. GNSS data collection documented the elevation, distance, time, speed, course, and position. The analysis of the video files was carried out by the first author of the study over a period of 10 months, by dedicating 8 h a day to this task. In total, close to 484 h of video files were analyzed. Each GNSS record was annotated in an Excel spreadsheet, categorizing activities according to the events (Table 2) observed in video files. Although this data processing option is resource-intensive [29,30], it was used for the sake of the accuracy provided. The work elements, called hereafter operational events observed in the video files, were defined and coded (Table 2), following a numerical coding scheme to facilitate the analysis. As such, each GNSS entry from the developed database was attributed to a given operational event by a dedicated code.

Table 2. Definition, codes, and description of the observed operational events.

Event	Abbreviation	Definition
Driving to the pre-skidding site	DET	Begins when the machine departs from the landing area and concludes upon arrival at the pre-skidding site, excluding any unrelated pauses.
Maneuvering at the pre-skidding site	MAN	Starts upon reaching the pre-skidding site and ends when the machine is positioned for pre-skidding. It excludes unrelated interruptions.
Pulling out the cable	POC	Begins when the operator deploys the winch cables and concludes when the worker managing the cable reaches the site of the logs to be secured. This step may occur multiple times within a complete skidding cycle and excludes any unrelated interruptions.
Attachment of the payload	APL	It begins when the worker handling the cable arrives at the pieces of wood to be attached and ends when the payload is attached to the cable. It can occur multiple times in a full skidding work cycle and excludes unrelated interruptions.
Pulling in the payload	PIP	Begins when the operator engages the winch and concludes once the payload arrives at the machine's rear part. This may occur multiple times within a complete skidding cycle, excluding any interruptions unrelated to the task.

Table 2. *Cont.*

Event	Abbreviation	Definition
Detaching the payload from the cable	DPC	It begins when actions to release the load are initiated and ends when the payload is detached from the cable. It can be repeated several times in a full skidding work cycle and excludes unrelated interruptions.
Attaching the payload for extraction	APE	Starts when the cables are released and ends when the payload is secured for extraction. It excludes unrelated interruptions.
Driving with the payload toward the forest access road	DFR	Starts when leaving the pre-skidding location and ends when reaching the landing. It excludes unrelated interruptions.
Detaching the payload toward the main forest haul road	DPR	Starts when operating the winch to release the cables and ends when the cables are free. It may involve a manual worker and excludes unrelated interruptions.
Maneuvering and bunching at the forest road	MBR	Starts with the first maneuver to bunch the wood and ends when the wood is bunched. It can be repeated several times in a full skidding work cycle and excludes unrelated interruptions.
Delays produced by the study	DS	Delays attributable to the study, such as the time spent to place and take down the dataloggers from the machines.
Delays produced by personal motives	DP	Delays caused by personal activities of workers.
Delays caused by mechanical reasons	DM	Delays due to mechanical problems with the machine.
Delays caused by operational reasons	DO	Delays due to operational organization problems, including waiting and performing other tasks not related to the skidding operations.

Following the analysis of video and GNSS data covering the period from 10 November 2020 to 25 August 2022, it was found that not all the collected data was usable due to several technical and quality limitations; therefore, an initial screening to filter and exclude unusable data was necessary (Table 3). This unusable data included instances where GNSS data was incomplete or entirely missing, making accurate synchronization with the video data impossible. However, data from those days was not completely eliminated; only the portions lacking the GNSS information were excluded. Additionally, data showing inconsistencies in the GNSS sampling frequency was also omitted. Moreover, the absence of video data was noted; on certain days, videos were missing or incomplete, which hindered a detailed analysis of the operations.

A final step in the data processing involved assessing the consistency and usability of the remaining event-based operational speed data. This analysis focused on all driving events, including driving to the pre-skidding site, maneuvering at the pre-skidding site, driving with a payload on the forest road, and maneuvering and bunching on the forest road. Consistent with the observed events in the field and in the video files, these events were characterized by interconnected acceleration behaviors, such as accelerating, maintaining a constant speed, and decelerating.

However, GNSS speed data collected by handheld instruments may suffer from inaccurate movement detection at low registered speeds. To refine the driving speed event data, we removed all instances showing speeds under 0.4 km/h (0.11 m/s) and greater than 15 km/h (4.17 m/s). The lower threshold was applied to correct for movement detection inaccuracies, while the upper threshold served as a reasonable limit to filter out unlikely speeds during tractor movements.

Table 3. Statistics of the overall, removed, and data kept for analysis.

Machine	Study Site	Useful Data (s)	Deleted Data (s)	Total Observed Data (s)	Useful Data (h)	Deleted Data (h)	Total Observed Data (h)
Skidder	SL1	84,561	3446	88,007	23:29:21	0:57:26	24:26:47
	SL2	25,251	50,547	75,798	7:00:51	14:02:27	21:03:18
	SL3	54,926	33,078	88,004	15:15:26	9:11:18	24:26:44
	SL4	26,497	42,256	68,753	7:21:37	11:44:16	19:05:53
	SL5	7716	7834	15,550	2:08:36	2:10:34	4:19:10
	SL6	58,793	27,547	86,340	16:19:53	7:39:07	23:59:00
	SL7	75,695	113,862	189,557	21:01:35	31:37:42	52:39:17
	SL8	170,790	94,478	265,268	47:26:30	26:14:38	73:41:08
	SL9	96,289	103	96,392	26:44:49	0:01:43	26:46:32
	SL10	122,324	20,819	143,143	33:58:44	5:46:59	39:45:43
	SL11	162,337	12,935	175,272	45:05:37	3:35:35	48:41:12
	SL12	163,178	4485	167,663	45:19:38	1:14:45	46:34:23
Farm tractor	SL13	22,770	120,102	142,872	6:19:30	33:21:42	39:41:12
	SL14	129,782	8615	138,397	36:03:02	2:23:35	38:26:37
Total		1,200,909	540,107	1,741,016	333:35:09	150:01:47	483:36:56

2.3. Data Analysis

Microsoft Excel® was used for data analysis, with the Real Statistics® add-on incorporated to expand the statistical analysis functionalities [31]. Two subsets were designed and used for the statistical analysis: the skidder dataset (hereafter called SK) and the farm tractor dataset (hereafter called FT). The analysis process was conducted in several stages, beginning with normality tests to determine the appropriateness of the statistical techniques to be employed. The D'Agostino–Pearson test, a robust tool for evaluating the normality of sample data, was utilized because our samples were very large. This test assesses skewness and kurtosis, providing a measure of how far the data deviates from the symmetry and shape of a normal distribution [32]. The choice of the D'Agostino–Pearson test was influenced not only by the sample size but also by the characteristics of the operational speed samples, which were marked by a high number of duplicate values (ties).

Subsequently, descriptive statistics were applied to the relevant speed variables of each machine dataset (SK and FT). These statistics provided a detailed view of the data distribution, which is essential for understanding the basic characteristics of the variables under study [33]. The results included count data, minimum and maximum values, standard deviation (SD), and mean and median values, all calculated for the driving events of both datasets. Statistical descriptors were complemented by histograms showing the data distributions on bin categories set at 1 km/h, along with a normal curve overlay developed in Real Statistics for Excel.

As the results of the normality tests and histogram analysis indicated a non-normal distribution, the Mann–Whitney U nonparametric test [34] was employed to compare the operational speeds. This test is suitable for unbalanced and non-normal datasets, as recommended in the statistical literature. Comparisons were carried out between each two events within the same dataset, as well as between corresponding events from different datasets. This approach allowed for differentiation between events on the same machine and across different machines, enabling greater flexibility in characterizing our data.

3. Results

3.1. Data Description

Table 4 displays the descriptive statistics for the operational speed dataset. All event-level datasets failed the normality test ($p < 0.05$, $\alpha = 0.05$), justifying the use of the median as a more robust measure of central tendency. The results highlight notable differences in the operational dynamics of each driving event within the skidding work cycle. For instance, driving to the pre-skidding site occurred at significantly higher speeds compared to driving with the payload to the forest road. For cable skidders, the median values for these events were 5.00 and 3.90 km/h, respectively, while for farm tractors, they were 6.00 and 3.60 km/h, indicating a significant difference between the machines, particularly for driving to the pre-skidding site. Additionally, maneuvering at the pre-skidding site consistently showed differences within the same machine, with a lower median speed observed during maneuvers carried out in the forest.

Table 4. Descriptive statistics of operational speed during driving events.

Dataset	Operational Event	Mean Value (km/h)	Median Value (km/h)	Standard Deviation (km/h)	Number of Observations	Result of the Normality Test
SK	Driving to the pre-skidding site (SK-DET)	5.40	5.00	3.42	185,950	No $p < 0.05$ $\alpha = 0.05$
SK	Maneuvering at the pre-skidding site (SK-MAN)	2.00	1.60	1.27	11,606	No $p < 0.05$ $\alpha = 0.05$
SK	Driving with the payload to the forest road (SK-DFR)	4.30	3.90	2.61	209,838	No $p < 0.05$ $\alpha = 0.05$
SK	Maneuvering and bunching at the forest road (SK-MBR)	2.40	2.00	1.89	29,809	No $p < 0.05$ $\alpha = 0.05$
FT	Driving to the pre-skidding site (SK-DET)	5.50	6.00	2.40	19,962	No $p < 0.05$ $\alpha = 0.05$
FT	Maneuvering at the pre-skidding site (SK-MAN)	2.60	2.20	1.74	539	No $p < 0.05$ $\alpha = 0.05$
FT	Driving with the payload to the forest road (SK-DFR)	3.70	3.60	1.65	31,400	No $p < 0.05$ $\alpha = 0.05$
FT	Maneuvering and bunching at the forest road (SK-MBR)	2.90	2.80	1.63	3175	No $p < 0.05$ $\alpha = 0.05$

Cable skidders appeared to be slower in maneuvering compared to farm tractors. Overall, the analyzed datasets contained 437,203 records for cable skidders and 54,756 records for farm tractors.

3.2. Comparison of Operational Speed

The summary statistics for the performance measured by speed comparisons of events are shown in Tables 5 and 6 for the skidder and farm tractor datasets. Considering the same operational event, the results obtained from the comparison of the machines are presented in Table 7.

Table 5. Speed comparison results for the moving events of the skidder dataset.

Reference Operational Event	Compared Operational Event	*p*-Value	Diagnostic of the Comparison Test
Driving to the pre-skidding site (DET)	Maneuvering at the pre-skidding site (MAN)	<0.05	Significant differences
Driving to the pre-skidding site (DET)	Driving with the payload to the forest road (DFR)	<0.05	Significant differences
Driving to the pre-skidding site (DET)	Maneuvering and bunching at the forest road (MBR)	<0.05	Significant differences
Maneuvering at the pre-skidding site (MAN)	Driving with the payload to the forest road (DFR)	<0.05	Significant differences
Maneuvering at the pre-skidding site (MAN)	Maneuvering and bunching at the forest road (MBR)	<0.05	Significant differences
Driving with the payload to the forest road (DFR)	Maneuvering and bunching at the forest road (MBR)	<0.05	Significant differences

Table 6. Speed comparison results for the moving events of the farm tractor dataset.

Reference Operational Event	Compared Operational Event	*p*-Value	Diagnostic of the Comparison Test
Driving to the pre-skidding site (DET)	Maneuvering at the pre-skidding site (MAN)	<0.05	Significant differences
Driving to the pre-skidding site (DET)	Driving with the payload to the forest road (DFR)	<0.05	Significant differences
Driving to the pre-skidding site (DET)	Maneuvering and bunching at the forest road (MBR)	<0.05	Significant differences
Maneuvering at the pre-skidding site (MAN)	Driving with the payload to the forest road (DFR)	<0.05	Significant differences
Maneuvering at the pre-skidding site (MAN)	Maneuvering and bunching at the forest road (MBR)	<0.05	Significant differences
Driving with the payload to the forest road (DFR)	Maneuvering and bunching at the forest road (MBR)	<0.05	Significant differences

Table 7. Speed comparison results for the moving events of the two machines.

Reference Operational Event for the Skidder Dataset	Compared Operational Event for the Farm Tractor Dataset	*p*-Value	Diagnostic of the Comparison Test
Driving to the pre-skidding site (DET)	Driving to the pre-skidding site (DET)	<0.05	Significant differences
Maneuvering at the pre-skidding site (MAN)	Maneuvering at the pre-skidding site (MAN)	<0.05	Significant differences
Maneuvering and bunching at the forest road (MBR)	Maneuvering and bunching at the forest road (MBR)	<0.05	Significant differences
Driving with the payload to the forest road (DFR)	Driving with the payload to the forest road (DFR)	<0.05	Significant differences

Supporting data for the interpretation of these results is included in Figure 2. The statistical comparison tests indicated statistically significant differences among the speed variables considered, highlighting distinctions among the operational events examined in this study. However, the shapes of the compared distributions differed significantly for the compared variables (Figure 2), which suggests two important considerations. Firstly, the results of the tests should be interpreted in the context of the metrics compared. Given that the shapes of the distributions were different, the results are valid only for the mean ranks, which were also distinct. Consequently, there was a difference in the location of medians for all comparisons.

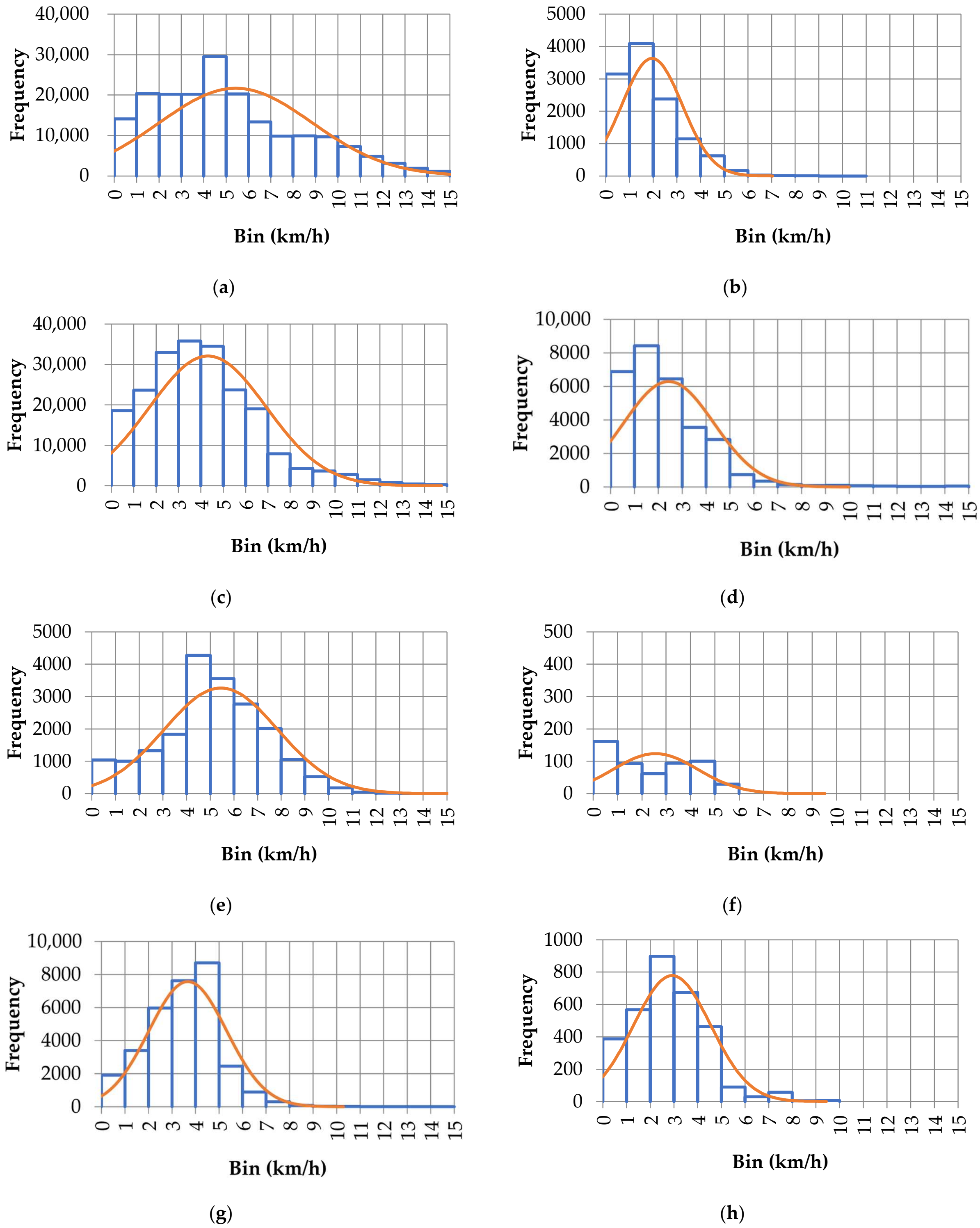

Figure 2. Data distributions characterizing the event-based operational speeds. Legend: (**a**) absolute frequency of observations for driving to the pre-skidding site for the skidder dataset (SK-DET), (**b**) absolute frequency of observations for maneuvering at the pre-skidding site for the skidder

dataset (SK-MAN), (**c**) absolute frequency of observations for driving with the payload to the forest road for the skidder dataset (SK-DFR), (**d**) absolute frequency of observations for maneuvering and bunching at the forest road for the skidder dataset (SK-MBR), (**e**) absolute frequency of observations for driving to the pre-skidding site for the farm tractor dataset (FT-DET), (**f**) absolute frequency of observations for maneuvering at the pre-skidding site for the farm tractor dataset (FT-MAN), (**g**) absolute frequency of observations for driving with the payload to the forest road for the farm tractor dataset FT-DFR, (**h**) absolute frequency of observations for maneuvering and bunching at the forest road for the farm tractor dataset (FT-MBR). Note: bin size was set at 1, and the curve in orange indicates the shape of a normal distribution by area matching over the sample data range.

Since the values of the U statistics were, in most cases, very large, they were not included in the data reported in Tables 5–7. However, these large values were specific to the data as the U statistic is accounting in calculation for the product of the number of observations present in every two samples compared.

4. Discussion

This work aimed primarily to characterize, at the elemental level, the operating speeds in cable skidding, focusing on the comparative performance analysis of specialized skidders and farm tractors configured for timber extraction. This objective was addressed through the development of a comprehensive, nationwide dataset.

Operational speed varied significantly across machine types and events, likely influenced by factors such as payload size, maneuvering complexity, terrain, and trail configuration and condition. For both skidders and farm tractors, the highest operational speeds occurred during unloaded travel to the pre-skidding site (DET), with median values of 5.00 and 6.00 km/h, respectively. At first glance, these results seem contradictory since farm tractors are typically considered less versatile and powerful and require specific adaptations for wood extraction [1,2]. However, our results reflect the conditions in which these machines were observed and are typically used; the farm tractors operated under easier conditions, such as flat and dry trails, while the skidders were assessed in rough conditions, including steep and muddy trails.

Consequently, the differences in power and versatility between the machines are reflected in the operational speeds when driving with a payload to the forest road, which showed a higher value for cable skidders (3.9 km/h) compared to farm tractors (3.6 km/h). Maneuvering events for both machines also indicate notable differences. Maneuvering in the forest was characterized by lower operational speeds, although farm tractors appeared to perform better in this regard as well. However, their higher performance can again be attributed to more favorable local operational conditions, with at least one example where the terrain at the pre-skidding site was flat. In contrast, cable skidders often maneuvered by driving forward and backward to position themselves adequately for pre-skidding. In many cases, this was coupled with constrained space for maneuvering, resulting in lower speeds.

Regarding the significant differences in operational speed at the landing, these can also be attributed to the types of maneuvers carried out by the two machines. Cable skidders, for instance, are typically used to bunch the wood with the front blade [2], whereas farm tractors generally lack this functionality; thus, their maneuvers consisted only of regular driving to place the payloads along the forest road, while cable skidders executed both types of maneuvers. This was reflected in our descriptive data, showing median speeds of 2.0 km/h for cable skidders and 2.8 km/h for farm tractors during such events.

The present results correspond closely with those observed in recent related research. Borz et al. [24] documented average driving speeds of 3.04 km/h without load and 3.25 km/h with load in skidding operations under low-access timber skidding conditions, values that align with those from this study, particularly in sites where operational conditions were particularly challenging. The lower speeds observed in farm tractor operations also corroborate the results of Borz and Mititelu [18], who reported on farm tractor performance in flat terrain skidding using Zetor tractors. Additionally, our event-level comparisons agree with the findings of Öztürk et al. [17], who emphasized the significant time share of loaded travel and the influence of extraction distance on overall productivity. Collectively, these comparisons validate the reliability of our results and situate them within the broader empirical context of timber skidding.

Most previous studies addressing the performance of skidding operations relied on limited amounts of data, which is understandable given the resources required to conduct them conventionally [7]. From this perspective, this research has both benefits and drawbacks. One benefit is that it encompassed most of the relevant operational conditions, as it relied on hundreds of thousands of recorded entries spanning multiple machines, forest and terrain conditions, trail conditions, seasons, and silvicultural prescriptions. This extensive coverage increases the statistical power of our estimates and enables nuanced analyses across event types and machine configurations. Moreover, the use of synchronized video and GNSS data allows for accurate temporal delineation of events, something that conventional time-motion methods often lack [29,30]. Accordingly, our dataset reflects real-world variability in forest operations, enhancing its relevance for operational planning and modeling. Including both farm tractors and specialized skidders allows for a comparative analysis seldom found in the literature, thereby contributing to discussions on appropriate equipment deployment for varying terrain and harvest intensities.

Despite the advantages of GNSS monitoring, its use as a proxy for real-time operational speed has inherent limitations. Factors such as canopy cover [35,36], terrain-induced occlusion [37,38], and satellite geometry [39,40] can reduce positional accuracy or cause signal loss, particularly in mountainous or densely forested areas. This issue was noted in our dataset and has also been described by Strandgard and Mitchell [26], who reported signal degradation on sloped terrain due to satellite occlusion. Furthermore, GNSS-derived speed captures only horizontal displacement, omitting events such as winching pauses or short maneuvers, unless paired with additional sensors (e.g., vibration or engine telemetry). Keskin et al. [41] further determined that low-cost GPS receivers offer acceptable horizontal accuracy but perform poorly in elevation measurements and under low-speed or intermittent movement, which are common in skidding operations.

Additionally, the speed latency of commonly used handheld GNSS devices [42], along with their inability to detect motion at low speeds, further complicates the problem and introduces uncertainty in the results. Accordingly, we have established credible speed thresholds to refine our dataset before statistical analysis, primarily to ensure valid estimates. For lower speeds recorded by GNSS devices, we have set a cutoff at 0.4 km/h to accurately reflect sub-events of maneuvering, which involve repeated acceleration and deceleration. While this threshold is purely based on an educated guess, it theoretically reflects the real, eye-detectable movement of the wheels at very low speeds. For higher speeds, we implemented rationing, as most advanced machines typically cannot operate at speeds exceeding 15 km/h [25]. Additionally, factors such as the experience of the operators [43], the slope [44,45], and changing conditions of the trails [46,47] may influence the event-based operational speed. Therefore, our approach of documenting data through video recording could serve as an effective strategy for reducing bias in speed estimates.

Moreover, the exclusion of data with irregular sampling intervals and our reliance on synchronized video recordings for annotation limited the usable portion of the dataset. However, this approach likely increased the certainty and validity of our estimates regarding operational speed. Nonetheless, when applied with proper filtering and validation, GNSS remains a valuable tool in modern time studies, enabling scalable, non-invasive analysis and supporting the derivation of movement-related metrics such as travel distances and delay durations.

The study was also influenced by limited interactions between the machines and their operational environments. Observations of farm tractors in steep terrain were scarce, primarily because these machines are generally unsuitable for work on slopes. Similarly, winter data for farm tractors were not captured, although existing literature suggests that on flat terrain, snow cover has minimal impact on speed [18]. Some high-quality GNSS data had to be discarded due to irregular sampling or missing video annotations, highlighting the importance of robust hardware and redundancy in data collection protocols, which can be enhanced in the future.

Unlike most previous studies that relied on GNSS monitoring of skidders primarily for automated time studies or productivity estimates under limited or controlled conditions [26,28,48], the novelty of this work lies in the development of robust figures of operational speed derived from a very large and finely documented dataset that systematically covered a broad spectrum of operational conditions. By integrating GNSS speed profiles across varying terrains, slopes, and accessibility levels, our study extends beyond the conventional scope of productivity modeling and provides a statistically sound representation of operational speed that captures the inherent diversity of skidding operations. This contribution ensures that the results are not constrained to a narrow set of circumstances but instead reflect the variability of real working conditions, thereby offering a stronger empirical foundation for operational planning and future modeling efforts [42].

Future studies should prioritize expanding sensor integration (e.g., using engine telemetry, accelerometers, and other types of sensors, i.e., [49]) to obtain increasingly reliable data for operational speed in skidding. This is because the reliability of GNSS data can be verified when accurate reference data is available to establish cut-off thresholds. These approaches could improve experimental estimates of operational speed. Additionally, seasonal and terrain diversification, particularly for farm tractors, would enhance the generalizability of the findings. Furthermore, leveraging machine learning for automated annotation could reduce reliance on synchronized video, thereby streamlining future large-scale studies [26,28,48].

5. Conclusions

This study provides a detailed characterization of operational speeds in cable skidding using a uniquely large and diverse dataset, offering novel insights into the performance of both specialized skidders and farm tractors under real field conditions. By analyzing GNSS-derived speed profiles across annotated work elements, it confirms that operational speed is highly influenced by machine and event type, with statistically significant differences observed within and between machines. The methodology, combining GNSS data with video-assisted event classification, demonstrates a scalable and objective approach for operational speed studies in forest operations, whereas the results reflect the condition and performance of the currently used machine fleet. These findings have direct implications for both science and practice: they provide a reliable empirical foundation for predictive modeling of skidding performance, support data-informed decision-making in equipment selection and forest operations planning, and highlight the value of integrating digital tools in forest operations research. Moreover, the results advocate for the continued development of sensor-based systems to improve accuracy and coverage, particularly in complex or variable environments.

Author Contributions: Conceptualization, S.A.B.; methodology, S.A.B.; validation, M.C.Z.V.; formal analysis, M.C.Z.V.; investigation, M.C.Z.V.; resources, S.A.B.; data curation, S.A.B.; writing—original draft preparation, S.A.B. and M.C.Z.V.; writing—review and editing, S.A.B. and M.C.Z.V.; visualiza-

tion, S.A.B. and M.C.Z.V.; supervision, S.A.B.; project administration, S.A.B.; funding acquisition, S.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Forest Administration—RNP Romsilva, grant number 4522/14.05.2020. The APC was waived. Part of this work was supported by two grants of the Romanian Ministry of Education and Research, CNCS—UEFISCDI, project number PN-IV-P8-8.1-PRE-HE-ORG-2023-0141, and project number PN-IV-P8-8.1-PRE-HE-ORG-2024-0186, within PNCDI IV, which supported data storage and the computing resources used in this study.

Data Availability Statement: The main data are included in this paper. The database may be released upon a reasonable request to the corresponding author of the study.

Acknowledgments: The authors acknowledge the support of forest regional directorates selected as study areas and the National Forest Administration—RNP Romsilva for the logistical support during data collection.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviation

Acronym	**Definition**
GNSS	Global navigation satellite system
SK	Skidder
FT	Farm tractor
U	Mann–Whitney U statistic
M	Mean
SD	Standard deviation
KM	Kilometers
H	Hour
S	Second
SL	Study location
IMU	Inertial measurement unit
DET	Driving to the pre-skidding site
MAN	Maneuvering at the pre-skidding site
POC	Pulling out the cable
APL	Attachment of the payload
PIP	Pulling in the payload
DPC	Detaching the payload from the cable
APE	Attaching the payload for extraction
DFR	Driving with the payload to the forest road
DPR	Detaching the payload at the forest road
MBR	Maneuvering and bunching at the forest road
DS	Delays caused by the study
DP	Delays caused by personal reasons
DM	Delays caused by mechanical reasons
DO	Delays caused by operational reasons

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