Trailer Overturning during Wood Transportation: an Experimental Investigation of Effects of Trailer Joint Point and Frame Structure

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Abstract

Trailers may increase the risk of tractor overturn during wood transportation in dangerous conditions. In this work, tests were carried to simulate a trailer rollover using three two wheel tractors and a crawler tractor and three trailers (two single-axle and one two-axle), all of their combinations moving downhill along the path on a short dirt road. The trailers were always loaded with the same load of logs cut at a length of about 1.5 m and put transversely to the longitudinal axis of the trailer. During each test, the following parameters were measured: the lateral dragging of the rear wheels/crawler of the tractor, the ground detachment of the rear upstream wheel/crawler and both the longitudinal and transversal strains (released over the tractor hooking system) produced by the trailer overturn. The study highlighted that the bi-axle trailer structure with a turntable steering had the best performances compared to the single-axle in terms of safety during trailer overturning. Independently of the trailer type considered in this work, a tied load is more dangerous than a load restrained only by steel struts, because during the overturn the load forms a single unit with the trailer mass, which increases the transversal and longitudinal strain.

Keywords: trailer structure, forestry, rollover, safety

1. Introduction

In the European Union (EU 28) in 2010 there were 12.2 million farms (with many small family farms) with around 5% of European workers involved (Eurostat 2014): this rate is not entirely correct because in agriculture there are many seasonal, part-time and irregular workers. In the period 2008–2014 in agriculture, forestry and fishing both the fatal accidents and the fatal accident rate (cases for 100,000 workers) diminished, but they were always high (Table 1). It is, furthermore, difficult to imagine a constant decreasing trend, because the fatal accidents are very variable in time; for example, it was observed by the Eurostat data that the fatal accidents decreased from 591 to 484 from 2008 to 2009, but in 2010 they increased again to 583.

The most common severe accidents in agriculture involve machineries and vehicles (also during repair and maintenance works), animals and falling from height (Eurostat 2014). The tractor is the main cause of occupational fatalities in agriculture (Lee et al. 1996): in the US in 1998, 32% of fatal injuries in agriculture were machinery-related accidents (Myers 2002) and many fatalities are due to tractor rollover (Erlich et al. 1993, Bernik and Jerončič 2008, HSE 2015, INAIL 2015).

Among all the agro-forestry tasks, tree and forestry works are considered high risk activities, with the sector having high fatal and injury rates (HSE 2015, INAIL 2015): manual and mechanical logging are among the most hazardous operations because operators work with potentially dangerous machines and use vehicles running through rough and sloped terrains (Blombäck et al. 2003). They are, moreover, exposed to the effects of bad weather and tasks are physically demanding: the long and repetitive nature of the work causes a range of health problems, including severe back pain

Table 1 Fatal accidents at work in some economic sectors in 2008 and 2014 (EU 28), source Eurostat data

	Fatal accidents 2008	Fatal accident rate 2008	Fatal accidents 2014	Fatal accident rate 2014	Absolute variation (fatal accidents)	Absolute variation (fatal accident rate)
Agriculture, forestry and fishing	591	8.06	536	5.81	–55	–2.25
Construction	1258	7.44	782	6.08	–476	–1.36
Transportation	711	6.75	622	5.84	–89	–0.91
Manufacturing	837	2.37	574	1.78	–263	–0.59
Human health and social activities	44	0.23	68	0.3	24	0.07

(HSE 2015). Also, in this case, the highest risk is due to tractor overturning: high tractor center of gravity and stability loss causes accidents which are often fatal, as observed by several authors (Maybryer 1952, Knapp 1968, Cole et al. 2006, Myers et al. 2009). A high number of accidents in hill and mountain areas are due to tractor overturning in sloped fields (Springfeldt 1996). The expected tractor overturn may be sideway or rearward (Kim and Rehkugler 1987).

There are two types of stability:

⇒ static stability – when a tractor is not moving

⇒ dynamic stability – during tractor movement.

Accidents usually occur when the tractor is moving. The key factors affecting the dynamic stability (Spencer and Gilfillan 1976) are both exogenous (environment dependent: slope, washboards, stones, rough terrain, potholes, ground obstacles) and endogenous (driver dependent: forward speed, driving style, slip, tiredness). Hunter (1991) established that more than 55% of the total tractor rollover accidents were caused by exceeding tractor limitations due to steep slopes, high speeds, and rough terrain. Moreover, the overturn risk could increase in presence of additional masses fitted on the tractor such as ballast, towed implements, and trailers (Yisa et al. 1998): the safety of larger vehicles is a matter of concern because they usually have large bodies with a high center of gravity and high loading capacity (Chou and Chu 2014).

Many studies have been carried out on the tractor-trailer stability and many simulations and mathematical models have been studied concerning both the static and dynamic stability, with focus on automotive sector (Chisholm 1979a, Blythe 2007, Mai et al. 2008, Barbieri et al. 2014). Moreover, the studies carried out on agricultural tractor stability were based on laboratory tests (Karkee et al. 2011, Guzzomi 2012, Ahmadi, 2013, Baker et al. 2013, Mazzetto et al. 2013, Previati et al. 2014), while in this case, the study was performed in the field.

In the agroforestry sector, there are many studies regarding the tractor stability (Davis 1974, Chisholm 1979b, Song 1989, Ahmadi 2011, Gravalos et al. 2011, Franceschetti et al. 2014, Li et al. 2014, Li et al. 2016), but there are only very few studies concerning the tractor-trailer stability analysis in forestry (Melemez et al. 2013, Manzone and Balsari 2014, Manzone 2015). Bietresato et al. (2015) proposed a methodological approach for the evaluation of an agricultural wheeled tractor equipped with different implements while operating on sloping hillsides.

The combination of the slope and uneven ground are limiting factors for a safe use of tractor in steep terrain and the use of a trailer may worsen the situation, especially during transport of heavy and unstable loads, such as logs (Pereira et al. 2011). Moreover, in some cases, the use of trailers may be dangerous because in presence of a little traction, the trailer can push the tractor off the road because of its small mass compared to the gross mass of the trailer (Lindroos and Wasterlund 2014). A solution to this problem is the use of trailers equipped with motor axles. In this case, the gross mass of the trailer improves the traction of the combined vehicles (i.e. tractor plus trailer). Recently, at the University of Turin, an innovative electronic control system for motorized axles has been developed (Manzone and Balsari 2015, Manzone 2015), able to synchronize the forward speed of the trailer to that of the tractor, independently of the tractor type used. Nevertheless, the frame structure of the trailer and its articulation point with the tractor may have a fundamental role in the trailer traction and in the convoy stability, especially when driving on sloped terrain.

Wood transportation using low-powered tractors with little trailers (single-axle or two-axle) is a common practice in the Italian alpine West Regions, characterized by steep and rough terrains. In this area, small scale logging companies with obsolete tractors and equipment are spread (Spinelli et al. 2013). The target of these companies, however, is to guarantee wood regeneration and to optimize the environment resiliency, ensuring the operator safety.

For these reasons, the aim of this research was to analyze the potential strains on the tractor caused by the trailer overturning. The trailers rollover tests were carried out using a wooden wedge during the convoy moving downhill. In detail, the effects of the trailer joint point (longitudinal and transversal strains, tractor rear wheel detachment from the ground) on the trailer overturning during wood transportation were analyzed, using different types of combination of tractors and regular trailers.

2. Materials and methods

2.1 Machines

Tests were carried out with two 2WD and one crawler tractors (named respectively #1, #2 and #3, Table 2).

To avoid the tractor mass influence on the system (tractor and trailer) stability, all the tractors used in the tests had a similar mass of about 1.5 t each, driver mass included (64 kg). The differences between the wheeled tractors were the wheel dimensions and total width (Table 2). All tractors were equipped with ROPS and seat belts. Different tractor types were chosen to analyze the trailer strain over the tractor structure.

Three trailers were used: two single-axle trailers (hereafter A and B) and one two-axle trailer (hereafter C) with steering turntable. They had a load floor 3 m long and 1.5 m wide, while the height of the load platform was about 750 mm. The trailers had the same wheel track and their tires had the same dimension (195 R14). The single-axle trailers were different in the hooking height of the towing eye: 0.35 and 0.75 m (half width of the load floor), respectively. The two-axle trailer was coupled to the tractor at the height of 0.35 m (Table 3).

The trailers had the rotating towing eye and were hauled to the tractor with a »fork« system (Fig. 1).

Table 2 Tractors characteristics

	Same Puledro (1)	Fiat 312R (2)	Itma Nike 320 (3)
Power, kW	23.68	22.52	25.51
Mass, kg	1433	1462	1514
Propulsion system	Wheels	Wheels	Tracks
Driving wheel	2	2	–
Rear wheel type	280/85–24	280/85–28	–
Front wheel type	5.00–15	5.50–16	–
Wheelbase, m	1.50	1.77	–
Overall width, m	1.38	1.81	1.23

* Does not include the mass of the driver (64kg)

** Measure calculated in correspondence with the propulsion wheels

Table 3 Trailers characteristics

	Single-axle (A)	Single-axle (B)	Two-axle (C)
Trailer mass, kg	235	240	330
Flatbed width, m	1.50	1.50	1.50
Flatbed height, m	0.75	0.75	0.75
Flatbed length, m	3.00	3.00	3.00
Wheel dimension	195 R14	195 R14	195 R14
Hooking height, m	0.35	0.75	0.75
Centre of mass*, m	1.27	1.28	2.33

Fig. 1 Tractor coupling »fork« system

2.2 Environment characteristics

Tests were carried out on a short dirt road (about 15 m), which connects a municipal road with a private dirt road. The path was not traced along the line of maximum slope, but transversal to the hillside. The average slopes of the path were about 30% longitudinal and 20% transversal. The path with these characteristics was chosen because there was a flat area that could simplify the maneuvers of the trailer re-overturn. Furthermore, this horizontal plane was useful for removing wood and consequently for reloading the trailer with the overturned logs.

2.3 Trailer rollover simulation

The trailer rollover simulation occurred with the convoy moving downhill along the path and placing an artificial obstacle in front of the trailer wheels. The use of an artificial obstacle was necessary to make the test repeatable. The obstacle was made of a wooden wedge (100 mm height, 300 mm length and 200 mm width). To ensure the tractor driver safety during the trailer rollover, the tipping point of the trailer was identified in a point where the tractor was already in the flat area (at the basis of the identified path).

Furthermore, to improve the test safety, a rope anchorage was placed between the base of a tree upstream the track and the frame of the tractor rollover protection system (ROPS). The first end of the rope was fixed to the ROPS using a knot, while the second end was rolled around the base of the trunk where a second operator kept this end of the rope in his hands. In this way, the second operator let the rope slide around the trunk during the tractor forwarding. In emergency situations (e.g. overturning of the trailer), the second operator promptly intervened and prevented the tip-over of the tractor, stopping the rope sliding (technique commonly used to control the fall of large branches during pruning in tree-climbing) (Fig. 2).

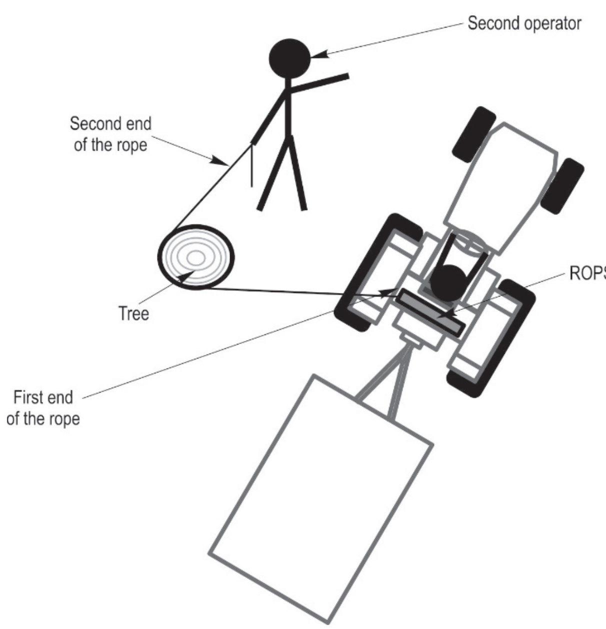

Fig. 2 Scheme of safety anchorage used during tests

During all the tests, the trailers were loaded with the same logs of about 1.5 m length and placed transversely to the load platform. The trailer gross masses (wooden and trailer weight) were equal to the tractor mass (1500 kg). This choice was the result of a survey carried out in some Italian forestry yards where, in extreme sloped conditions (with a high risk of trailer overturning), the trailer gross mass does not exceed the tractor mass. Logs had a regular shape (cylinder) with an external diameter between 120 mm and 260 mm. Each log was numbered with a numeric code and, each time the load was applied, logs were placed on each trailer in the same identified position. This precaution was taken so that the same load distribution and the same weight on the towing eye were provided during all the performed tests: 543.7±1.2 kg for the two single-axes (A and B) and 9.4 kg for the bi-axle (C). In the case of trailer C, the precise number is ascribable to the unique drawbar weight.

Tests were carried out both with the load held in place only by steel supports fixed at the two ends of the load floor (front and rear) and with the load tied by two ropes placed diagonally to the longitudinal axis of the trailer.

The average forward speed was always around 3 km h^{-1} and three overturning repetitions were performed for each trailer and for each tractor type (27 tests).

2.4 Measurements and instruments

During each test, measurements were made of:

⇒ lateral deviation (side slipping) of rear wheels/crawler of the tractor

⇒ detachment of rear upstream wheel/crawler from the ground

⇒ longitudinal and transversal strains (released over the tractor hooking system) produced by the trailer overturn.

The lateral deviation (side slipping) of the tractor wheels/crawler was measured using a graduate steel ruler (1 mm precision). This measurement was performed starting from the rubber tire crampons until the end of the sideslip on the ground.

The detachment height of the wheel/crawler from the ground was evaluated using a measurement device (fixed on the mudguard) made with a plastic graduate strip (1 mm scale) rolled on a reel without return spring. The end of the strip was linked to a steel support (1 kg mass), sliding on the ground by a small rope linked to another support fixed to the tractor frame. Before the start of the test, the strip was stretched: this condition was maintained until the

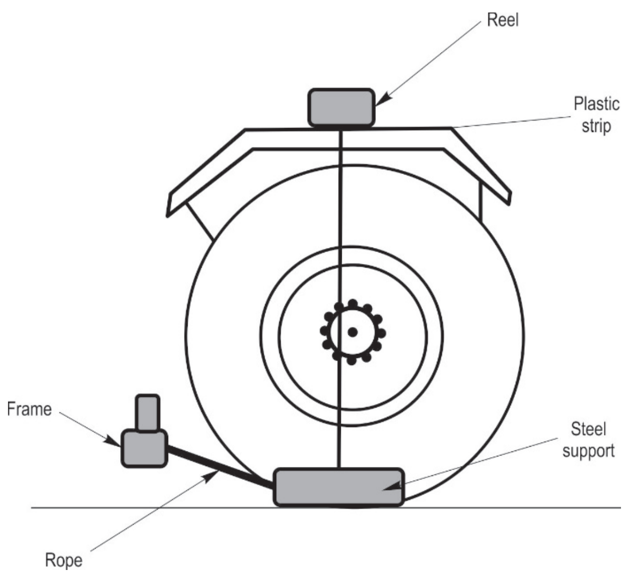

Fig. 3 Scheme of the system used to measure the detachment height of the wheel/crawler from the ground

trailer overturning. At this occurrence, the strip extended in function of the wheel/crawler detachment: the strip length difference was the detachment height of the wheel/crawler from the ground (Fig. 3).

The transversal and longitudinal strains were calculated using a specific device based on mechanic pendulum. It was built connecting a mechanic pendulum (100 mm length) to a goniometer (120 mm diameter) by a centre hinge (Fig. 4): a weight (20 g mass) was joined at the unrestrained extremity of the pendulum. To measure the maximum transversal and longitudinal strains, two metallic pointers (free to move) were added to the same hinge (Fig. 4): at the beginning of each test, these pointers were aligned to the pendulum (point zero). Two mechanics pendulum were used during the tests: the first positioned orthogonally to the tractor forward speed (to measure the transversal strain), the latter parallel (to measure the longitudinal strain). In all the test conditions, each device was fixed by two bolts in the centre of the ROPS top (Fig. 4).

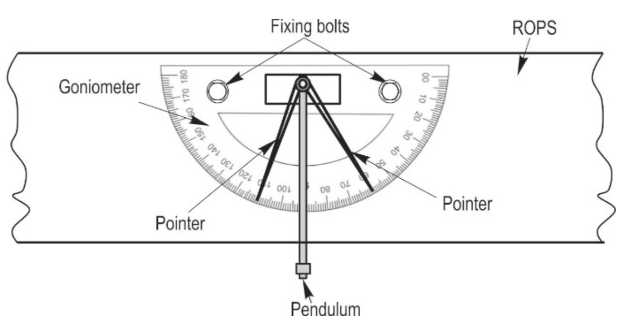

Fig. 4 Mechanic pendulum system used in the test

Positive measurements were clockwise. In detail, front longitudinal measured strains were positive, negative at rear. Transversal strains were positive at left, negative at right.

The goniometer enabled the measurement of small displacements in linear unit (mm) (Timoshenko and Gere 1976): for this reason, in data elaboration, only linear measurements were considered.

2.5 Data processing

Data processing was performed using Microsoft Excel and IBM SPSS V. 22.0 Statistic package. The ANOVA and post-hoc Tukey tests were performed in order to evaluate possible differences between the tested trailers, tractors and loose or tied loads (Keppel and Wickens 2004). Tukey test was chosen for its high power for this data distribution (Tukey 1949). Tests differences were evaluated considering α=0.05.

3. Results

3.1 Lateral deviation and ground detachment height of the tractor wheels/crawler

The highest lateral deviation of the tractor propulsion system was produced by the single-axle trailer with the lowest hooking point (A). It always caused

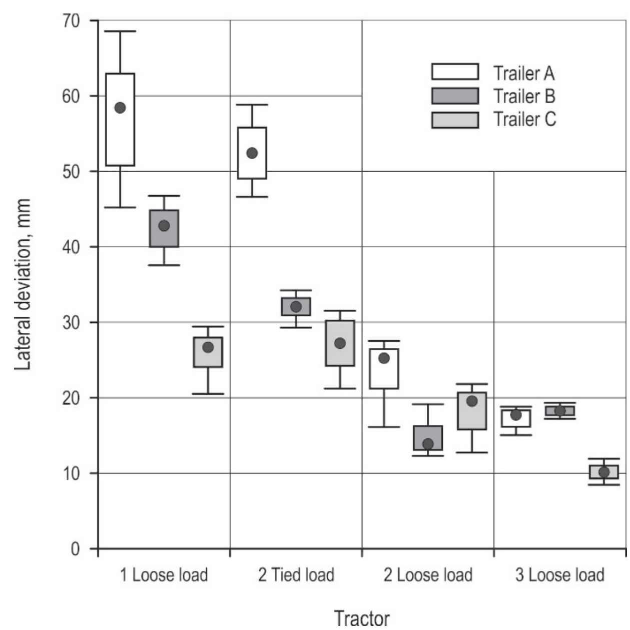

Fig. 5 Box & whisker graph of lateral deviations measured on the tested convoy configurations during trailer overturning

Table 4 Lateral deviation and ground detachment measured on the tractor wheel/crawler during trailer overturning

Load	Tractor	Trailer	Wheel / crawler lateral deviation, mm				Wheel/crawler ground detachment, mm			
			Mean	Min	Max	SD	Mean	Min	Max	SD
Loose	1	A	57	45	68	11.5	27	24	31	3.8
		B	42	37	46	4.5	3	0	8	4.6
		C	26	21	29	4.2	0	0	0	0.0
	2	A	23	16	27	5.9	29	23	34	5.7
		B	15	13	19	3.2	0	0	0	0.0
		C	17	11	21	5.3	0	0	0	0.0
	3	A	16	14	18	2.1	14	11	17	3.0
		B	18	17	19	1.0	0	0	0	0.0
		C	9	7	11	2.0	0	0	0	0.0
Tied	2	A	52	45	58	6.5	38	33	42	4.6
		B	32	29	34	2.5	0	0	0	0.0
		C	27	21	32	5.5	0	0	0	0.0

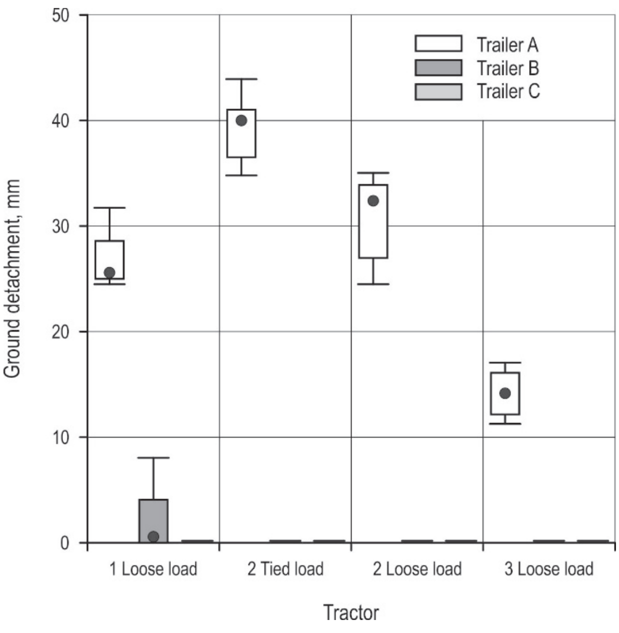

Fig. 6 Box & whisker graph of the rear wheel (or crawler) ground detachment measured on the tested convoy configurations during trailer overturning

the lifting (of some millimeters) of the tractor rear axle in all the tractor overturning tests (Table 4).

Lateral deviations were in a range between 7 and 68 mm (Fig. 5): the trailer A showed the highest lateral deviations in the wheeled tractors from 14 to 68 mm (in the crawler tractor the single-axle trailers A and B had about the same values, around 18 mm) while, with the exception of tractor 2 with the loose load, the bi-axle trailer (C) had the lowest lateral deviation values (never higher than 32 mm). If the load was tied, the same tractor (#2) presented higher lateral deviation data (about twice, independently of the trailer type).

Tractor #2 and #3 showed the lower lateral deviation data of the wheel (or crawler).

The single-axle trailer with the low hook (A) always caused the highest detachment values of the rear wheel (or crawlers) from the ground (Fig. 6), with values around 30 mm in the wheeled tractors with the loose load (about 40 mm with the tied load): the single-axle trailer with the high hook (B) caused only a slight detachment value of 8 mm in tractor #1. The bi-axle trailer never caused any wheel or crawler detachment from the ground, independently of the tractor and load type.

3.2 Longitudinal strain

Similar results for the strain measured on the tractors were found in the single-axle trailer with the high hook (B) and in the bi-axle trailer with steering turntable (C): here the longitudinal strain (the pointer movement along the goniometer during the trailer rollover) produced swinging intervals lower than 15 mm (Table 5). Different values were obtained for the single-axle trailer with the low hook (A): in this case the longitudinal strain was higher and varied in a wider interval between 6 and 20 mm.

Also in the case of the total longitudinal strain, the trailer with the low hook produced the highest values (Fig. 7). Differently from the tests discussed in para-

Table 5 Longitudinal strains measured on tractors during trailer overturning

Load	Tractor	Trailer	Front, mm				Rear, mm			
			Mean	Min	Max	SD	Mean	Min	Max	SD
Loose	1	A	11.0	10	12	1.00	–13.0	–12	–14	1.00
		B	6.7	6	8	1.15	–7.0	–6	–8	1.00
		C	6.3	5	7	1.15	–8.3	–7	–9	1.15
	2	A	11.7	10	14	2.08	–7.3	–6	–8	1.15
		B	4.7	4	5	0.58	–5.7	–5	–6	0.58
		C	5.7	4	7	1.53	–7.3	–6	–8	1.15
	3	A	6.7	6	7	0.58	–6.3	–6	–7	0.58
		B	4.3	4	5	0.58	–3.3	–3	–4	0.58
		C	4.7	4	5	0.58	–4.3	–4	–5	0.58
Tied	2	A	15.0	12	17	2.65	–17.7	–16	–20	2.08
		B	11.7	11	13	1.15	–12.0	–10	–14	2.00
		C	11.3	10	12	1.15	–10.7	–10	–11	0.58

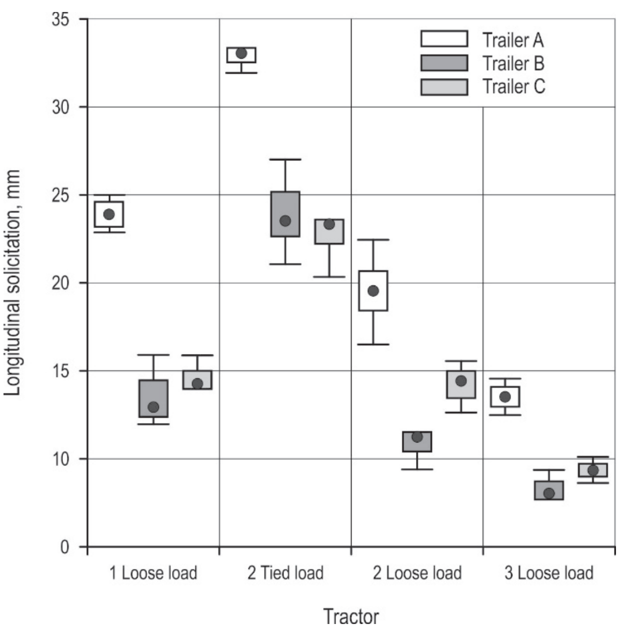

Fig. 7 Box & whisker graph of the rear wheel (or crawler) ground detachment measured on the tested convoy configurations during trailer overturning

graph 3.1, the bi-axle trailer (C) always produced higher total longitudinal strains than the single-axle trailer with high hook (B) for loose load. The highest longitudinal strains were observed with the tied load, independently of the trailer type. The crawler tractor best absorbed the strains caused by the trailer overturning (Fig. 7).

3.3 Transversal strain

The ransversal strain was generally higher than the longitudinal one (Table 5 and Table 6): also in this case the single-axle trailer with low hook (A) caused the highest boosts on the tractor (Fig. 8). The trailer with the low hook (A) generated transversal strains always 30 % higher than the same trailer type with the high

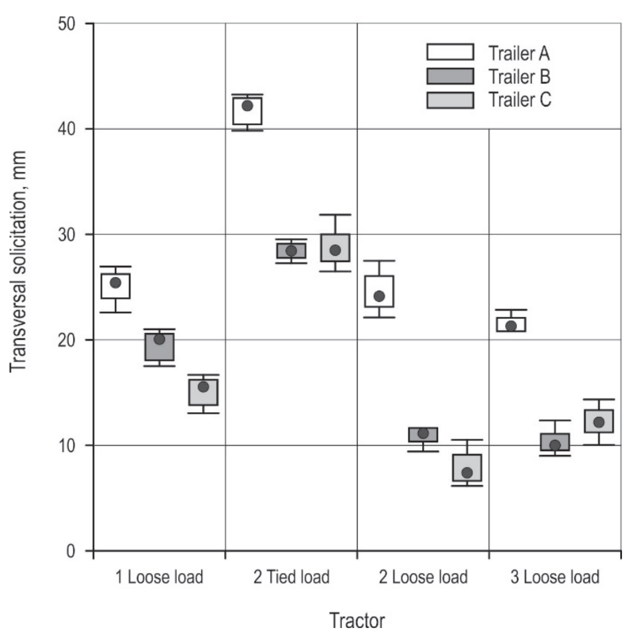

Fig. 8 Box & whisker graph of transversal strains measured on the tested convoy configurations during trailer overturning

Table 6 Transversal strains measured on tractors during trailer overturning

Load	Tractor	Trailer	Left, mm				Right, mm			
			Mean	Min	Max	SD	Mean	Min	Max	SD
Loose	1	A	15.0	14	16	1.00	–10.3	–11	–9	1.15
		B	11.0	10	12	1.00	–8.7	–9	–8	0.58
		C	7.7	6	9	1.53	–7.7	–9	–7	1.15
	2	A	11.0	10	12	1.00	–13.3	–15	–11	2.08
		B	7.0	6	8	1.00	–3.3	–4	–3	0.58
		C	4.7	4	6	1.15	–4.0	–5	–3	1.00
	3	A	11.7	11	12	0.58	–10.0	–11	–9	1.00
		B	7.0	6	8	2.08	–4.3	–5	–4	0.58
		C	6.0	5	7	2.08	–7.0	–8	–6	1.00
Tied	2	A	20.3	16	23	3.79	–21.3	–24	–20	2.31
		B	14.3	12	16	2.08	–13.7	–15	–13	1.15
		C	14.3	13	16	1.53	–14.3	–16	–12	2.08

hook (B): there are even peaks of 100% when the tractor #2 was used, with the loose or tied load (Fig. 8).

For this parameter, too, the highest values (between 26 and 43 mm) were obtained when operating with the tied load (Fig. 8).

3.4 Influence of tractor and trailer structure on measured parameters

Results highlighted that the tractor structure had an important role in the trailer overturning.

The ANOVA procedure evidenced tractor similarities in only one parameter, the ground rear wheel/crawler detachment, mainly influenced by the trailer type (Table 7).

In absolute terms, even though all the tractors had the same mass, the crawler and the bigger wheeled tractors guaranteed higher resistance forces to the strains provided by different trailers (Table 8). In detail, tractor #2 and #3 showed similar values in lateral deviation and in both longitudinal and transversal strain data. Some significant differences among the three tractor types were observed in the ground detachment of the rear wheels or crawlers (Table 8).

Statistical analysis showed similar results for all types of tested trailers only in lateral deviation tests

Table 7 ANOVA statistical analysis of tractors

		SS	df	AS	F	Significance
Ground detachment	Among groups	156.911	2	78.456	0.529	0.596
	Inside groups	3560.136	24	148.339	–	–
	Total	3717.047	26	–	–	–
Lateral deviation	Among groups	3834.741	2	1917.370	20.875	<0.0001
	Inside groups	2204.444	24	91.852	–	–
	Total	6039.185	26	–	–	–
Longitudinal strain	Among groups	259.556	2	129.778	7.765	0.003
	Inside groups	401.111	24	16.713	–	–
	Total	660.667	26	–	–	–
Transversal strain	Among groups	154.741	2	77.370	2.269	0.025
	Inside groups	818.444	24	34.102	–	–
	Total	973.185	26	–	–	–

Table 8 Tukey test for different parameters of tractors tested

Tractor code	N	Lateral deviation, mm		Ground detachment, mm	Longitudinal strain, mm		Transversal strain, mm	
3	9	14.44	–	4.67	9.89	–	14.78	–
2	9	18.33	–	9.78	14.33	14.33	15.33	–
1	9	–	41.44	9.78	–	17.44	–	20.11
Significance		0.670	1.000	0.651	0.074	0.259	0.150	0.230

Subset for $\alpha=0.05$

Table 9 ANOVA statistical analysis of trailers

		SS	df	AS	F	Significance
Ground_detach	Among groups	3146.156	2	1573.078	66.131	<0.0001
	Inside groups	570.891	24	23.787	–	–
	Total	3717.047	26	–	–	–
Lateral_dev	Among groups	983.630	2	491.815	2.335	0.118
	Inside groups	5055.556	24	210.648	–	–
	Total	6039.185	26	–	–	–
Long_strain	Among groups	324.222	2	162.111	11.564	<0.0001
	Inside groups	336.444	24	14.019	–	–
	Total	660.667	26	–	–	–
Trans_strain	Among groups	682.741	2	341.370	28.208	<0.0001
	Inside groups	290.444	24	12.102	–	–
	Total	973.185	26	–	–	–

Table 10 Tukey test for different parameters of trailers tested

Trailer code	N	Lateral deviation, mm	Ground detachment, mm		Longitudinal strain, mm		Transversal strain, mm	
C	9	17.22	0.01	–	12.44	–	12.33	–
B	9	25.00	0.89	–	10.56	–	14.11	–
A	9	32.00	–	23.33	–	18.67	–	23.78
Significance		0.099	0.922	1.000	0.541	1.000	0.533	1.000

(Table 9): for the other parameters, the p value was always lower than 0.0001.

The analysis of statistical data showed that the single axle trailer with high hook (B) and the bi-axle trailer with steering turntable (C) produced the same statistical results (Table 10).

4. Discussion

The study highlighted that trailers with an »articulate« drawbar (turntable steering), apart from giving lower lateral deviation data and resulting in the absence of ground detachment of the rear wheels (or crawlers), also produced the lowest strain (longitudinal and transversal) to the tractor during its overturning. The higher absolute values observed in longitudinal solicitations for the bi-axle trailer are only attributable to the higher trailer tare and, consequently, to the higher resistance force exercised by the trailer during the overturning (rear longitudinal strain values of trailer C are presented in Table 5).

The best performance of the bi-axle trailer (C) could be explained with the higher number of junction joints (4 swivel joints) of the steering turntable system

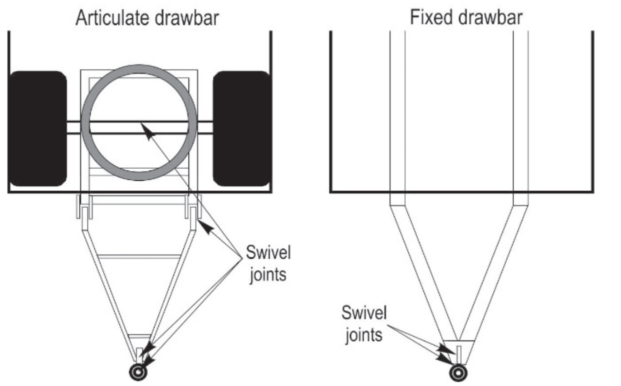

Fig. 9 Swivel joints in different drawbar types

compared to a drawbar fixed to the trailer frame (2 swivel joints, Fig. 9).

In fact, the articulate drawbar (Trailer C) is able to compensate different types of critical points during the trailer overturning (support points, coupling point, etc.) (Fig. 10a). In contrast, a drawbar fixed to the trailer frame (Trailer A) could generate an overturning force on the coupling point of the tractor, mostly, if this latter showed a height lower than half of the load floor width of the trailer (Fig. 10b). This can cause a higher instability of the tractor, especially if it has no brakes on front axle and, as a consequence, there is a higher possibility of overturning. On the contrary, if the height of coupling point of the tractor is equal to half of the trailer width (Trailer B), no overturning forces are generated on the tractor itself (Fig. 10c).

Unfortunately, these results are in contrast with the »guidelines« usually adopted in forestry activities, where trailers with fixed drawbar are preferred to

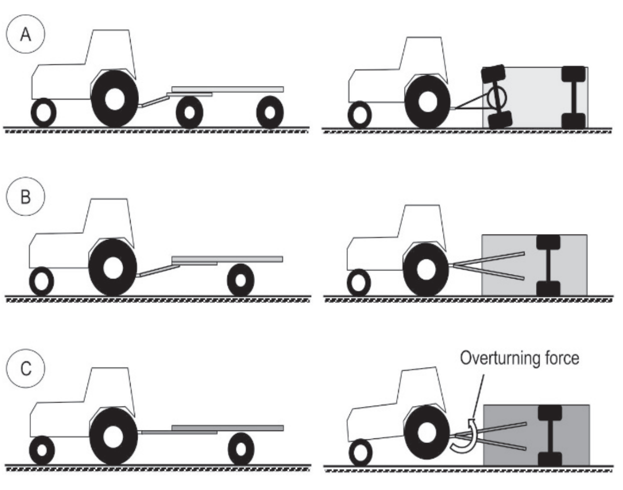

Fig. 10 Scheme of trailer overturning on flat ground in different configurations

trailers with an articulate drawbar (Manzone 2015). In fact, the use of the first trailer type guarantees a higher traction force because part of the trailer load is discharged on the tractor and because it shows a greater simplicity in maneuvering due to minor articulation points of the convoy structure.

It was moreover observed that the loose load guaranteed a better safety during the trailer overturn: the tied load is dangerous because during the trailer overturning its mass is added to the trailer mass and causes higher strains to the tractor.

Concerning the tractor structure, the wide system propulsion tracks guaranteed the best absorption of the trailer strain caused by its overturning: in fact, the crawler tractor had the best performances, as opposed to the tractor with the smallest wheels.f

Other Authors (Marinello et al. 2013) simulated and tested a double steering trailer prototype composed o two single-axle trailers, which is a good solution for the transport of high length logs (more than 8–10 m long) on narrow and steep forest roads in order to reduce the curve radius and to improve the convoy maneuverability. Nevertheless, on the basis of the results of this study, this prototype may produce the same strains as the single-axle during the trailer overturning (although it seems to have a bi-axle structure) because the first module of the prototype has a fixed single-axle drawbar.

5. Conclusions

The study highlighted that the bi-axle trailer structure with a turntable steering had the best performances compared to the single-axle trailer in terms of safety during trailer overturning. These results are not entirely in line with forestry practices that usually suggest the use of a single-axle trailer because it discharges part of the load on the coupled tractor (Spinelli et al. 2013).

Independently of the trailer type considered in this work, a tied load is more dangerous than a load restrained only by steel struts, because during the overturn the load forms a single unit with the trailer mass, which increases the transversal and longitudinal strain.

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Received: June 28, 2016
Accepted: October 3, 2017

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