TRACTOR LENGTH INFLUENCE ON TRAFFIC SAFETY AND EFFICIENCY




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Abstract

A commonly seen vehicle combination on the European road network is the tractor and semi-trailer combination with a maximum total length of 16.5 meters. The legal limitation on the total length of the combination has led to a short tractor to make space for more goods on the trailer. Concerns have been raised that the shortness of the tractors may have a negative consequence on traffic safety and efficiency. In this scope, a set of tractor and semitrailer combinations have been simulated in severe conditions to investigate how wheelbase of the tractor, coupling length, fifth wheel lubrication, and road surface conditions affect the vehicle response. Whenever meaningful, a comparison was made with a Nordic combination, as well as a B-double combination. The overall result of the simulation study is that a tractor and semitrailer is a stable combination which outperforms the Nordic and B-double combinations in the studied situations. Furthermore, the wheelbase of the tractor seems to have a minor effect on the performance of the vehicle combination.

Keywords: Wheelbase, Stability, Braking in curve, Lane change, Hill climbing, Tractor and semitrailer

1. Introduction

EU regulation limits the length of tractor-semitrailers to 16.5 m. However, in Nordic countries, longer tractor-semitrailers are allowed on the roads, where tractors are used, with larger wheelbase than their European counterparts. In said countries, there have been concerns that shorter tractors have poorer performance and are involved in more accidents than the Nordic equivalents, especially in winter conditions. To investigate these concerns, the dynamic performance of two and three axles tractor-semitrailers are simulated and compared in this paper. Nordic (truck-dolly-semitrailer) and B-double (tractor-link trailer-semitrailer) combinations which are common in Nordic countries are used as references for dynamic performance.

Problems with semitrailer combinations in wintertime have been reported primarily in Norway. The focus has however been on foreign vehicles, which to a very large extent are 16.5-meter tractor semitrailer combinations, compared to Norwegian heavy goods vehicles (HGVs). In 2016 the Institute of Transport Economics, TØI, concluded based on accident data that foreign HGVs driving in Norway had 3 times higher risk for single-vehicle accident compared to Norwegian HGVs. (Nævestad et al. 2016). They also found that foreign HGV drivers were more likely to trigger a fatal accident, had twice the risk for a head-on collision, and nearly twice the risk of a collision with a vehicle driving in the same direction compared to Norwegian HGV drivers. Statistics also indicated that foreign heavy vehicles were overrepresented among the vehicles that got “stuck” while driving on winter roads, as 33 % of the HGVs which were “stuck” on winter roads were foreign, while foreign HGVs only accounted for 6 % of the average domestic transport in Norway in 2009-2012. In comparison, 11 % of the HGVs involved in personal injury accidents in Norway were foreign. Nævestad et al. highlight two risk factors to be important for explaining these results:

1. experience with/competence on Norwegian roads
2. winter driving

Granlund and Thomson (2016) argue that the so-called EU-trailer consisting of a tractor and semitrailer combination of length 16.5 meters may be more prone to accidents on Nordic slippery winter roads compared to traditional Nordic straight trucks with drawbar trailers. They have carried out computer simulations of a double lane change maneuver using the commercial software Trucksim where the stability of an EU-trailer was investigated on three different levels of road friction, μ. The model used a fifth wheel without friction. They report stable maneuvering at 80 km/h for μ=0.5, while the lower road friction level of μ=0.25 leads to jack-knifing at 67 km/h in laden condition and at 61 km/h for the unladen condition. Lowering the road friction even more to μ=0.10 reportedly led to jack-knifing already at 24 km/h for both laden and unladen condition. As no comparisons are made with other vehicle combinations or tractor-semitrailer combinations with other dimensions it is difficult to draw any conclusions regarding potential stability problems of the EU-trailer combination from these simulations.

2. Method

Under focus are the short tractor vehicle combinations, their vehicle dynamics properties, and how these properties compare to other combinations (Nordic and B-double). To address the posed questions, computer simulations are created for models representing the different vehicle combinations.

The validity of the simulated outcomes is largely determined by the validity of the models used in the simulation, where validity is the extent to which the modelled vehicles can reproduce the behavior of real world vehicles. For these investigations, the models of the vehicles (and their interaction with the road) were validated against test track recordings of real vehicles. They could be regarded as state-of-the-art models with respect to the dynamic behavior in maneuvers where the lateral dynamics are of importance.

The validity of the used models is still an issue, despite being well established. To mitigate consequences of incorrect predictions of the models, a scheme is applied where the relative performance between the different vehicles is used, rather than the absolute outcomes of the simulation of a single vehicle. This approach allows one to focus on the proper representation of relevant dynamic phenomena rather than prediction of exact outcomes.

The models of the vehicles are simulated in maneuvers to illustrate their different performance, and physical quantities are used to quantify the performance. The maneuvers are controlled by a model of a driver tasked with maintaining desired trajectory and speed profile. All vehicle combinations use the same driver model as a means to assess the vehicle performance, rather than mimicking a driver behavior of a real human driver.

Similar arguments can be stated for the maneuvers themself. The single lane change for example is a maneuver used in numerous studies to assess vehicle performance. Even though the single lane change is a maneuver and an event that occurs frequently in traffic, the purpose of using it here is not to simulate the traffic event. Instead, the maneuver is performed in a relatively extreme manner to produce a severity that makes the different combinations react differently. For example, the brake in curve maneuver with engine brake, it is designed to provoke a jack-knife for the tractor semitrailer combinations. The performance is then how much brake force (retardation) the combination can stand before it becomes unstable.

The ability to negotiate an uphill climb is assessed through a different set of models, where the engine power and the road friction are the main components. The maneuver is given by the slope that the combination can negotiate.

3. Models and conditions

Six tractor semitrailer combinations were used to investigate the impact of tractor wheelbase length impact on the combination performance. Three combinations had varying length of tractor wheelbase. Another set of three combinations was added to reflect the variety of bogie axles configurations: pusher, tag and two driven. For benchmarking, two longer combinations were added: the Nordic combination (truck + dolly + semitrailer) and the B-double (tractor + link trailer + semitrailer). All the vehicle dimensions are taken from an OEM (Volvo) and are commonly found vehicles on the road network, today. However, they may not represent the frequency of vehicles with these dimensions seen in traffic. For further details on their geometry see (Bruzelius et al. 2020).

The dynamic models of these vehicle combinations are based on an OEM vehicle model library implemented in MATLAB Simscape, further described in (Hebib and Dam 2019), and have been used extensively in e.g., the performance based standard project (Kharrazi et al.

2017). The models include rigid bodies of the vehicles with compliance in the tyres (vertically), suspension, and torsion in the chassis-frame of the tractors (and truck). The cabins are suspended relative to the chassis. A similar open-source implementation of this model library can be found in (Sedran et. al. 2016).

The following factors were considered in the investigations in attempt to understand their interaction with the dynamic effects of a short wheelbase on the tractor:

- Tyre to road surface friction, to emulate summer and winter conditions
- The lubrication of the fifth wheel, which interconnect with seasonal conditions
- Cargo loading condition, to find a worst-case scenario

The load cases for all the combinations are given in the two tables below.

Table 1 Axle loads of the tractor semitrailer combinations for three different load cases. The driven axles are given in italic.

		Tractor load on axle [tones]			Semi-trailer [tones]	Total weight [tones]
Combination	Load case/axle	1st	2nd	3rd	All axles	
TR4x2long_ST3	Unloaded	5.353	*2.9868*	-	1.830	13.829
	Front loaded	7.260	*10.802*	-	7.313	40.000
	Rear loaded	6.849	*9.117*	-	8.011	40.00
TR4x2medi_ST3	Unloaded	5.288	*3.051*	-	1.830	13.890
	Front loaded	6.772	*11.290*	-	7.313	40.00
	Rear loaded	6.452	*9.514*	-	8.011	40.000
TR4x2short_ST3	Unloaded	5.215	*3.125*	-	1.830	13.890
	Front loaded	6.195	*11.545*	-	7.420	40.000
	Rear loaded	6.010	*9.956*	-	8.011	40.000
TR6x2pusher_ST3	Unloaded	5.327	1.653	*2.480*	1.830	14.950
	Front loaded	6.6717	5.536	*8.304*	6.481	40.000
	Rear loaded	6.191	4.067	*6.101*	7.880	40.000
TR6x2tag_ST3	Unloaded	4.941	*2.783*	1.855	1.830	15.070
	Front loaded	5.377	*9.148*	6.099	6.459	40.000
	Rear loaded	5.212	*6.740*	4.494	7.851	40.000
TR6x4_ST3	Unloaded	5.364	*2.470*	*2.470*	1.830	15.795
	Front loaded	6.637	*7.195*	*7.195*	6.324	40.000
	Rear loaded	6.156	*5.408*	*5.408*	7.676	40.000

Table 2 Axle loads of the reference vehicles, the Nordic combination and the B-double.

		Tractor load on axle [tones]			Dolly converter/ Link-trailer [tones]	Semi-trailer [tones]	Total weight [tones]
Combination	Load	1st	2nd	3rd	1st and 2nd	All axles	
TK6x4_DY2_ST3	Unloaded	5.500	1.750	1.750	2.056	1.830	18.600
	Front loaded	6.564	8.718	8.718	8.789	7.474	64.000
	Rear loaded	6.564	8.718	8.718	7.983	8.011	64.000
TR4x2_LT2_ST3	Unloaded	5.283	3.028	-	3.014	1.830	60.000
	Loaded	6.738	11.101	-	9.044	8.024	60.000

To assess the combinations' ability to follow a clear path with minimum off-tracking, a lane change maneuver was used. To quantify tendency for jack-knifing and trailer swing behaviors of the vehicle combinations brake in a curve maneuver were used (all wheel braking and engine braking). The risks for getting stuck in an uphill were assessed through the PBS measures startability and gradeability.

The lane change is a standard maneuver used to assess performance of vehicle dynamics. There are different standards, e.g. (ISO 14791:2003), specifying how such a maneuver should be performed. A lane change is performed with a steering input in constant speed, and displacing the vehicle combination by the width of a lane, on a straight road. For this study we will try to provoke the vehicle combinations under certain conditions (road grip etc), which may correspond to an extreme change of lane that you typically do not find on everyday traffic.

Braking in curve was another maneuver used to assess the vehicle combination performance. Braking in curve has previously been used in the literature to assess vehicle combinations tendencies to jack-knifing, see for example (Chen, Shieh Y-A (2010)). In (Ma, Peng (1999)), a worst-case maneuver is derived based on optimal control for jack-knifing situations. The conclusion is that both steering and braking is required, but the braking plays a more central role. Two different braking in curve maneuvers are considered. In both maneuvers a curve is used and a constant braking torque is applied on all or driven wheels. In the first maneuver, only engine/retarder brake is applied on the drive wheels. The basic idea behind this maneuver is that for an engine braking tractor, the semitrailer will try to push the tractor in the tangent of curve. On the tractor, the push for the trailer generates a force which as a component perpendicular to the tractor axles, causing it to lose lateral grip and cause a jack-knife as the trailer continues to push. An alternative maneuver will also be tested where all the vehicle combination wheels are braking simultaneously. This may cause the trailer to lose grip and a trailer swing may occur.

It should be stressed that both these maneuvers are simulated using simple models lacking many of the available safety functions that exist on tractors of today. A simple ABS system is implemented, but no other safety functionality for engine braking is implemented. This implies that jack-knifings and trailer swings may occur in these simulations where safety functions could have intervened in real situations. The main objective of the simulations is to illustrate the susceptibility of the different vehicle architectures to such conditions.

4. Results

This section presents the simulation results from the lane change and braking in curve maneuvers and finally for the uphill driving.

4.1 Lane change

The maximum speed with which the vehicle can pass the maneuver, was not only decided based on the tractor following the defined path, but also on the trailers following the tractor with limited offtracking. Considering a 3.5 m lane width and a vehicle width of 2.5 m, an offtracking of 1 m is the maximum allowable offtracking that will not result in encroaching into the adjacent lane or road shoulder. Thus, the simulations were repeated with increasing speed until the vehicle failed to follow the defined path or the offtracking exceeded 1 m. The speed values in winter conditions are provided in Table 3.

When limiting the offtracking, the maximum speed range is from 61 to 79 km/h. The Nordic combination has the lowest passing speeds since it reaches the offtracking limit at lower speeds. It is followed by the tractor-semitrailer with tag axle. The offtracking for the tractor-semitrailer combinations are in similar range, the vehicles with tag and pusher axle have a bit lower offtracking. The Nordic combination, B-double and tractor-semitrailer with tag axle have lower passing speeds compared with the tractor-semitrailer with short wheelbase. The other vehicles have a bit higher passing speed than the short tractor-semitrailer, but the difference is lower than 5%, i.e. it is not substantial.

For the three tractor-semitrailers ‘short’, ‘medi’ and ‘long’ the wheelbase has been changed, with a fixed fifth wheel position to respect the 16.5 meter of total length. Another possibility is to move the fifth wheel and keep the distance to the rear axle fixed. In that case the performance in the lane change will be almost unchanged between the three combinations.

Table 3 Maximum possible speed [km/h] in the single lane change maneuver with limited offtracking in winter conditions

Cond	Case	TR4x2long_ST3	TR4x2medi_ST3	TR4x2short_ST3	TR6x2pusher_ST3	TR6x2tag_ST3	TR6x4_ST3	TK6x4_DY2_ST3	TR4x2_LT2_ST3
Rear loaded	Lubricated	75	75	75	75	74	76	63	69
	Half lubricated	75	74	72	73	71	74	62	70
	Non lubricated	72	71	69	69	67	71	61	69
Front loaded	Lubricated	75	75	74	76	74	76	63	69
	Half lubricated	74	73	72	72	69	73	62	70
	Non lubricated	71	70	68	67	63	69	61	69
Unloaded	Lubricated	79	79	78	79	78	79	66	76
	Half lubricated	78	78	79	78	78	79	66	76
	Non lubricated	78	78	77	78	77	78	65	77

4.2 Braking in curve

Two braking in curve maneuvers are considered, engine/retarder brake on drive wheels and all-wheels braking. These maneuvers are only simulated for the winter condition.

Engine brake case

In this maneuver only engine and retarder brake on the drive axles are applied to induce jackknife in a tight curve with radius of 300 m. The simulation is repeated with increasing level of braking torque, with a step of 500 Nm, until a jackknife happens or an upper limit of 19 kNm is reached. The measure used for comparison is the engine/retarder brake level that will cause a jackknife. The simulations were performed for two cases of with/without anti-lock braking.

The simulation results are summarized in Table 4. The 6x2 tractor-semitrailers with anti-lock system did not end up in a jackknife. The applied braking torque will be limited by the drive axle load, which is lower for the 6x2 tractors, compared with the rest of combinations, which may explain the lack of jackknife. However, the anti-lock function for engine brake is not as robust as ABS, and therefore the case without anti-lock is more important to consider. Note that although the jackknife inducing engine braking torque is lower for unloaded cases, the achievable deceleration is comparable for the unloaded and loaded cases.

The rear loaded vehicles have a bit worse performance compared to the front-loaded vehicles and the tractor-semitrailers with 2-axle will jackknife at lower levels of engine/retarder brake torque compared with the ones with 3-axle. The jackknifing for the 2-axle tractors happens at similar levels of engine brake and the wheelbase length has minor effects on it.

A comparison between the combinations with fixed distance between fifth wheel and the rear axle revealed minor difference. Hence, the fifth wheel position has a minor effect on the risk of jackknifing while the loading conditions have a greater impact.

Table 4 Engine brake torque [kNm] which causes a jackknife in winter conditions

Cond	Case	TR4x2long_ST3	TR4x2medi_ST3	TR4x2short_ST3	TR6x2pusher_ST3	TR6x2tag_ST3	TR6x4_ST3
without anti-lock	Rear loaded	9.0	9.0	9.0	10.0	11.0	13.0
	Front loaded	9.5	10.0	10.0	13.0	13.5	15.0
	Unloaded	3.5	3.5	4.0	3.5	4.5	6.5
with anti-lock	Rear loaded	11.5	11.5	12.0	>19	>19	18.5
	Front loaded	12.5	13.0	13.0	>19	>19	19.0
	Unloaded	5.0	5.0	5.0	>19	>19	8.0

All-wheel brake

In this maneuver the brakes are engaged for all wheels on each unit of the vehicle combination, when the vehicle is negotiating a tight curve with radius of 400 m. The same braking torque is applied simultaneously on all wheels. The simulation is repeated with increasing level of braking torque, with a step of 500 Nm, until the vehicle becomes unstable, or it slides off the road and cannot follow the path anymore.

The braking torque (per wheel) which causes instability for each vehicle and loading case, with and without ABS, is listed in Table 5. For the ABS-on case, sliding off the road is the cause for failure, but for the ABS-off case the cause for failure is mostly trailer swing.

For the unloaded cases without ABS, the applied braking torque which causes instability is the same for all vehicles and very low (1.5 kNm), due to the low axle loads and low friction force at winter conditions. This highlights the importance of a functioning ABS for the safe performance of the vehicles. The front loaded and rear loaded values for the ABS-off case are the same for each vehicle, but the front-loaded case is safer for the ABS-on case. The values are comparable between the vehicles. The reference vehicles and the tractor-combinations with 2-axle tractors can tolerate a bit higher braking torque before becoming unstable. Only minor differences can be seen between the performance of the tractor-semitrailer with short wheelbase and other vehicles, or none.

Table 5 Braking torque per wheel [kNm] which causes instability in winter conditions

Cond	Case	TR4x2long_ST3	TR4x2medi_ST3	TR4x2short_ST3	TR6x2pusher_ST3	TR6x2tag_ST3	TR6x4_ST3	TK6x4_DY2_ST3	TR4x2_LT2_ST3
ABS off	Rear loaded	4.5	4.5	4.5	4.0	3.5	4.0	4.5	4.5
	Front loaded	4.5	4.5	4.5	4.0	4.0	4.0	4.0	4.5
	Unloaded	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
ABS on	Rear loaded	5.5	5.5	6.0	4.5	4.5	4.5	5.5	6.0
	Front loaded	6.5	6.5	7.0	5.0	6.0	5.0	5.0	6.0
	Unloaded	5.0	5.0	4.5	5.0	4.5	5.0	6.0	4.5

4.3 Hill climbing ability

The six tractor semitrailer combinations and the heavier Nordic and B-train combinations were simulated using simple expressions. The engines were chosen such that the gross weight to power ratio is comparable across the combinations. The focus of the study is to investigate the performance influence on the wheelbase of the tractor. All results are presented in Table 6 and Table 7.

For the two truck trailer combinations with a tag and a pusher axle, the performance has been presented with the tag/pusher axle down and lifted, respectively. It should be stressed that for the front loaded and lifted cases the legal limit of axle load of 11.5 tons is exceeded for both the tag and the pusher combinations. This is also true for the lifted rear loaded tag case. The simulations should be seen in the light of this excessive load, and the performance should be evaluated accordingly.

It can be seen that the length of the tractor for a two-axle tractor does not have a major effect on the ability to negotiate an uphill. A minor positive effect can be observed with increasing wheelbase. The boogie equipped tractor combinations with only one propelled axle perform worse in all situations compared to the short two axles tractor combination. This is since the load on the propelled axle is reduced compared to the two axles one.

Table 6 The Gradeability results for the two surfaces (μ=0.75 and μ=0.25) and two speeds (80km/h and 40km/h)

Cond	Case	TR4x2long_ST3	TR4x2medi_ST3	TR4x2short_ST3	TR6x2pusher_ST3	TR6x2pusher_ST3 (Lifted)	TR6x2tag_ST3	R6x2tag_ST3 (lifted)	TR6x4_ST3	TK6x4_DY2_ST3	TR4x2_LT2_ST3
high μ [%]	Unloaded	7.35	7.35	7.35	6.76	6.76	6.7	6.7	6.37	8.22	7.68
	Front loaded	2.27	2.23	2.21	2.21	2.21	2.21	2.21	2.21	2.04	2.2
	Rear loaded	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.04	-
low μ [%]	Unloaded	3.07	3.18	3.3	2.04	3.73	2.47	6.43	5.41	2.78	2.04
	Front loaded	2.27	2.23	2.21	2.21	2.21	2.21	2.21	2.21	2.04	2.2
	Rear loaded	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.04	-
low μ, low speed [%]	Unloaded	4.18	4.28	4.4	3.06	4.75	3.49	7.45	6.38	3.6	2.81
	Front loaded	5.65	5.83	5.93	4.11	6.22	4.58	9.48	7.53	5.59	3.62
	Rear loaded	4.57	4.79	5.04	2.87	4.42	3.23	6.84	5.52	5.59	-

Table 7 Results of Startability for the two road surfaces (μ=0.75 and μ=0.25)

Cond	Case	TR4x2long_ST3	TR4x2medi_ST3	TR4x2short_ST3	TR6x2pusher_ST3	TR6x2pusher_ST3 (Lifted)	TR6x2tag_ST3	R6x2tag_ST3 (lifted)	TR6x4_ST3	TK6x4_DY2_ST3	TR4x2_LT2_ST3
high μ [%]	Unloaded	14.6	14.9	15.3	11.2	16.3	12.5	24.3	21.1	12.7	10.3
	Front loaded	16.3	16	15.9	14	15.9	15.4	15.9	15.9	9.94	10.6
	Rear loaded	15.4	15.9	15.9	10.3	14.9	11.4	15.9	15.9	9.94	-
low μ [%]	Unloaded	5.4	5.52	5.65	4.15	6.02	4.62	9.01	7.82	4.7	3.82
	Front loaded	6.9	7.1	7.22	5.19	7.54	5.72	11.2	8.99	6.81	4.63
	Rear loaded	5.7	5.95	6.22	3.81	5.54	4.21	8.22	6.76	6.81	-

Adding propulsion to second rear axle makes the combination perform better in almost all situations. This is due to the extra load the tractor introduces with the extra weight from the second rear axle and the powertrain parts, without losing the normal load to an unpropelled axle. However, this is a costly combination and is hence rare in traffic. For three axle tractors with liftable axles, the performance is on par or better than the short wheelbase two axle tractor combination for most of the cases. This is due to the extra load on the driven axle when the tag/pusher axle is lifted. Here, we have assumed that the load has not been altered when the axle is lifted. This results in a situation where the legal load limit per axle is exceeded (up to 56% over the legal limit for the tag front loaded case), hence, the performance improvements lifted tag/pusher axle versus the short axle combination should be considered in the light of this.

5. Discussion

In this paper, comparisons between the introduced vehicle combination have been performed through simulations. The objective of the study was to investigate how short vehicle combinations perform compared to longer ones, in extreme conditions. The extreme conditions were represented by a single lane change and a braking in a curve scenario. Sensitivity with respect to loading, fifth wheel lubrication and road slipperiness was investigated to highlight differences among the selected vehicle combinations.

The short combinations are made up of a tractor that propels the combination and a semitrailer attached to the fifth wheel of the tractor. A set of different configurations and dimensions were simulated and compared within as well as to two longer vehicle combinations, the Nordic and B-double combinations.

5.1. Traffic safety aspects

In the lane change maneuver, the shorter tractor semitrailer combinations perform relatively similar considering the offtracking and maneuver speed. When increasing the wheelbase in 4x2 tractors, some minor improvement in the performance can be seen, if the fifth wheel distance to the front axle is unchanged. However, if this distance is increased along with the wheelbase, the performance is not altered. This is likely due to that the reduced load on the front axle that comes with such a move. In comparison with the three axles tractors, the short 4x2 tractor combination performs slightly better than one of them and slightly worse than the other two. When comparing with the Nordic and B-double combinations, the tractor-semitrailer combinations perform better. This demonstrates that there is no clear disadvantage of the short tractor-semitrailer in comparison with the rest of studied vehicle combinations in a lane change maneuver. When it comes to instability while braking in a curve, the wheelbase does not seem to have a considerable influence on the vehicle performance either. For engine braking in curve, the three axles' tractors are superior in performance compared to the two axles ones. This is due to the advantage of a better load distribution on the propelled axles.

In general, the length of the tractor does not seem to have a large impact on any of the performance measures used in the report. It seems that the position of the fifth wheel has larger impact than the wheelbase, or more precisely the distance between the fifth wheel and the rear axle(s) of the tractor. This distance will have a direct connection to the load transfer from the semitrailer to the tractor's axles. To summarize, it is the combined influence of axle configuration, wheelbase, fifth wheel position and axle loads which determines a vehicle performance.

The overall performance of the tractor semitrailer combinations is that that they are very stable in dry weather conditions. They are not prone to instability modes, and the offtracking is limited in magnitude. In comparison, the Nordic combination is outperformed by all tractor semitrailer combinations in the study. The Nordic combination is more prone to instability and the offtracking can be a limiting factor. This is not merely due to its total length as the B-double, with the same total length, is a considerably more stable combination and close to the performance of the tractor semitrailers.

The lubrication of the fifth wheel seems to have a similar effect on all tested combinations, where the performance drops when lubrication level drops. The effect is minor for dry road conditions. For winter conditions the effect is noticeable, but still bounded. The effect is further amplified with the load on the fifth wheel. It should be stated though that the effect seems stronger than the wheelbase of the tractor on the performance. The simulation results do not suggest that the problem of unlubricated fifth wheels on short vehicle combination would cause more difficulties compared with other vehicle combinations. However, this is only considering the vehicle dynamics properties of the phenomena. Driver aspects may have a major influence on the severity of driving with poorly lubricated fifth wheels.

For the braking case, the importance of a properly working anti-brake lock mechanism is stronger than the effects of wheelbase. This is the case for all combinations and configurations and pronounced for slippery roads with empty or light loaded trailers. Hence, a requirement for properly working ABS systems could have a positive influence on the accident statistics.

It should be noted that the comparison here between the different vehicles is made in a context without a driver, and strictly limited to the vehicle dynamics properties and the differences in these between vehicle combinations. Certain combinations might be driven more frequently in certain environment, by certain operators and drivers that largely effect the frequency of accidents. Hence, combinations that are not necessary the safest may be less frequent in the accident statistics.

Another aspect to take in consideration is that the measures of performance used in the report do not reflect how hard or easy the combination is to maneuver for a human driver. Certain dynamic behaviors are easier to handle by human drivers, such as slow and early indications of instability as appose to abrupt changes and vehicle responses. Hence, it might very well be so that for example that the Nordic combination is easy to handle as it is predicable with its large offtracking, which makes the combination safe in real situations.

5.2. Ability to climb hills

The ability to climb hills is determined by the power of the engine and the available friction forces in the contact between the road and the tyres of the propelled axles. The friction forces that can be extracted are roughly direct correlated with the load on the axles that are propelled. Hence, given an engine that can produce enough power, the ability to negotiate an uphill is a matter of having proper tyres for the current conditions and as much load as possible on the propelled axle.

The simulation results show that if the tractor is equipped with tandem rear axles with only one driven axle, it suffers from reduced load on the driven axle. The allowed load on the tandem axles is not equal to twice the load allowed on a single rear axle. It is hence beneficial to load such that the unpropelled axle can be lifted. It should be noticed that if legislations allow for a temporary lift of boogie axles on tractors, the tables are turned and the 6x2 tractors with lifted axles perform better than the 6x2 tractors and the 6x4 with both axles down.

It should once more be stressed that the grip of the tyres is central to the ability to negotiate an uphill. A high load on the driven axle cannot compensate for bad tyres with low friction towards the road surface as the load is constrained by the carrying capacity of the road. Hence, the legislation on winter tyres on driven axles should have an impact on this problem.

The investigated 4x2 tractors show that the wheelbase difference has almost no impact on the performance. This is due to the geometrical fact that the load on the driven axles will not change significantly due to a longer wheelbase, for the same load on the semitrailer.

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