NOTE

Axle spacing and vehicle dynamics for European tractor-semitrailer combinations

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ABSTRACT
European tractor-semitrailer combinations typically have a relatively short spacing between the front and first rear axle for the tractor, motivated by the standardized type of semitrailer together with an overall restricted combination length. These combinations are notorious for their susceptibility to wintertime problems and incidents with traction loss and jack-knifing in harsh road conditions common in Scandinavia. Transport professionals have concurred that the main factor behind these accidents is the short tractor axle spacing. Some vehicle dynamics modeling and simulation investigations, however, assert that the role of tractor axle spacing is minor. One reason for these differing inferences may be the role of overall combination length in the context. Regulations in Scandinavia allow longer tractors than in Central Europe and most simulation studies only consider spacings for fixed overall length $16.5 - 17$ m. We calculated effective yaw moments of inertia for these axle spacings as well as for a longer, Scandinavian spacing to estimate its role for articulation dynamics of these tractor-semitrailer combinations.

KEYWORDS
Axle spacing; yaw; inertia; tractor-trailer; semitrailer; commercial vehicles; trucks.

1. Introduction

Tractor-semitrailer vehicle dynamics has been a longstanding subject to investigation by first-principles modeling and simulation, see e.g. [1,2]. Some of these studies have been adopted as guidelines for legislation concerning weights and dimensions for heavy vehicle combinations. However, transport economy, i.e., maximizing load space, as well as European Union transport policies appear to be the main factors behind current weights and dimensions for these heavy vehicles. Hence, during recent decades regulations for weight and length throughout Europe have evolved into a standard configuration for semitrailer combinations. This so-called *EU-trailer*, has an overall length of 16.5 m and a length of the trailer of 13.6 m. These dimensions, common to Central Europe but not to Scandinavia, strongly limit spacing between the steering and (first) rear axle.

Meanwhile, the enlargement of the European Union has extended the common transport market from Central and Eastern Europe into Scandinavia, multiplying the

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number of EU-trailers on the road in Scandinavia. Regrettably, these have also been involved in numerous incidents caused by traction problems and jack-knifing, particularly in harsh road conditions during wintertime. The Scandinavian transport professionals community by now widely recognize that the main cause of these accidents is the short axle spacing of the tractor. Field test have concluded that tractors having Scandinavian dimensions with longer axle spacing exhibit safer yaw dynamics less prone to jack-knifing. [3] Scandinavian transport authorities have responded to the situation with stricter winter tire requirements for heavy vehicles and at some point even considered wintertime traffic restrictions for EU-trailers.

2. Modeling and Simulation Studies

The role of axle spacing has been investigated through first-principles modeling and simulation. [2–4] Some of these studies have concluded its significance to be minor, a result which can be considered due to imposing the rigid condition of constant overall combination length $L_T < 17$ m. [2] Allowing the distance from the CG to the pivot point (kingpin) to increase, see Fig. 1, on the other hand, produces modeling results consistent with practice and previous findings [4].

Account should also be taken of the pivot point's non-linear friction, which can momentarily be very high and is of great importance in slippery road conditions. [5] The impact that a tractor unit's pivot point can have on driving dynamics is very complex and certainly underestimated in studies [2,6,7].

In dynamical simulations with different types of vehicle combinations, the standard ISO14791 [8,9] on how the assessment should be carried out is applied. The standard requires a test track with a simple lane change, divided into three parts, the middle of which produces lateral movement. However, the standard does not specify the length of the movement distance. In Swedish reports, a constant length of 70 meters has been adopted for the travel distance, without taking into account that vehicles with a longer axle spacing need a longer travel distance. [9] Hence, the results of the reports only describe how the examined vehicle combinations perform for a 70 m travel distance. Such a procedure risks discrediting longer axle spacings, in particular, if an unrealistic vehicle model is used in the simulations.

3. Influence of axle spacing on Effective Tractor Yaw Inertia

Consider a tractor of mass m_t with wheelbase L, center of gravity (CG) located at distance a from the front axle, and pivot position located at distance x_p from the front axle, see Fig. 1. The effective tractor yaw moment of inertia about the pivot point is

$$I_{p,t} = I_{CG,t} + \underbrace{m_t \left(x_p - a\right)^2}_{I_{PA}}, \tag{1}$$

where $I_{CG,t}$ denotes the tractor yaw moment of inertia about its center of gravity and I_{PA} is termed the parallel vertical axis contribution. Yaw inertia about the center of gravity is calculated formally through the integral below, which can be approximated

$$I_{CG,t} = \int_0^{m_t} r^2\left(m\right)\ \mathrm{d}m \approx k m_t L^2,\ k = 0.10, \tag{2}$$

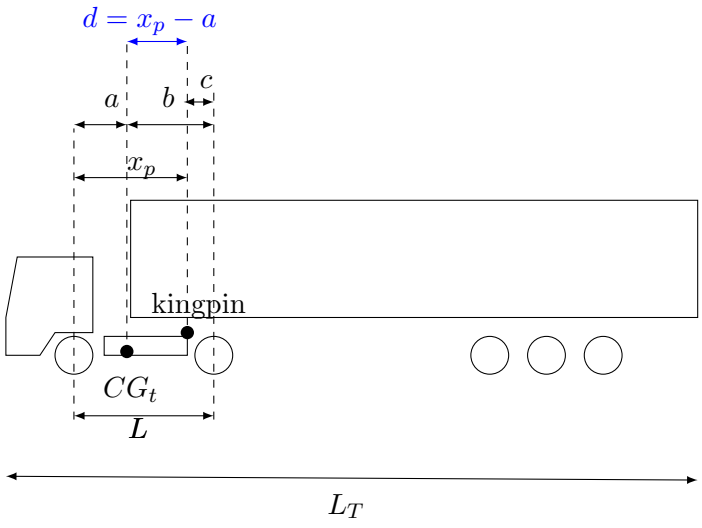


Figure 1. Notation and physical dimensions for the European tractor-semitrailer combination.

where $r\,(m)$ is the distance from the tractor CG to each mass element. The value adopted in (2) for the proportionality constant k was derived from published heavy-vehicle multibody models and commercial simulation models.

Combining (1) and (2) reveals that the influence of distance L, from the front axle to the first rear axle, on the effective tractor yaw moment of inertia about the pivot point is dual; directly through (2) and indirectly through $d = (x_p - a)$ in (1). However, as the latter is roughly the double of (2), this influence is significantly stronger. Moreover, there is the dependence of the tractor CG position on axle distance to consider, as follows.

3.1. Variation of Tractor CG Position with Axle Distance

Consider a two-axle tractor in Fig. 1 or similar three-axle configuration. The CG position determines the front axle-to-CG distance a in (1) and can be estimated from the data given by Bruzelius et. al [2]. These are the steer W_f, drive W_r and third W_t axle loads for the unladen tractor as well as the axle distance L and the interaxle distance L_i for the rear bogie, given in table 1.

Taking moments about the front axle gives

$$(W_f + W_r + W_t)\, a = W_r L + W_t\,(L + L_i)\,. \tag{3}$$

Defining

$$W_{\text{tot}} = W_f + W_r + W_t, \tag{4}$$

yields

$$a = \frac{W_r L + W_t\,(L + L_i)}{W_{\text{tot}}}. \tag{5}$$

Tractor configuration for semitrailer combination					
property	short 4×2	long 4×2	sh. 6×2	lg 6×2	17.5 m 6×4
m_t (kg)	8200	8500	9500	10000	10500
W_f (kg)	5215	5353	4941	5364	5500
W_r (kg)	3125	2987	2783	2783	2550
W_t (kg)	-	-	1855	1855	2550
L_t (m)	16.5	16.5	16.76	16.96	17.56
L_i (m)	-	-	1.37	1.37	1.37
L (m)	3.5	3.9	3.2	3.4	4.1
x_p (m)	3.135	3.135	3.4	3.6	4.2
a (m)	1.312	1.397	1.815	1.831	2.302
d (m)	1.824	1.738	1.585	1.769	1.898
$I_{CG,t}$ (10^4 kg m^2)	1.005	1.293	0.973	1.156	2.017
I_{PA} (10^4 kg m^2)	2.727	2.568	2.388	3.130	4.322
$I_{p,t}$ (10^4 kg m^2)	3.731	3.861	3.360	4.286	6.339

Table 1. Results for tractor inertia about the centre of gravity ($I_{CG,t}$), parallel-axis contribution to tractor intertia (I_{PA}) and effective yaw inertia ($I_{p,t}$). Dimensions are given in Fig. 1. Unladen weights are sourced from the report [2].

3.2. Implications for Articulation Dynamics

The articulation dynamics may be represented schematically, for effective yaw moments of inertia about the pivot for the tractor $I_{p,t}$ and for the semitrailer $I_{p,s}$, by

$$(I_{p,t} + I_{p,s})\,\ddot{\phi} = M_{\text{art}}, \tag{6}$$

where ϕ denotes articulation angle and M_{art} denotes the articulation moment generated by tire and inertial forces. An increase in tractor effective inertia from a longer axle distance reduces articulation angular acceleration for a given articulation moment. Consequently, this generally produces slower tractor yaw response, lower articulation-rate gain, reduced susceptibility to rapid jack-knife initiation as well as greater robustness during braking-in-a-curve manoeuvres.

4. Results for a set of axle distances

As a preliminary investigation into the role of axle distance for the effective yaw moment of inertia about the pivot coupling for European tractor-semitrailer combinations, calculations outlined in the previous sections were performed. These were done for a choice of configurations studied by Bruzelius and co-workers [2], namely a long and short two-axle (4×2) as well as a long and short three-axle tractor (6×2) and a three-axle tractor (6×4) with a longer wheelbase for overall length of 17.5 m. All tractors were coupled to a standard EU-trailer having the length 13.6 m. Further dimensions and weights according to Fig. 1 are given in Table 1 and its caption.

The conclusion in [2] that axle distance alone had a minor influence is fully consistent with the criterion used, i.e., performance on the 70 meter lane-change track. The simulations compared combinations where axle distance changes were accompanied by changes in axle configuration, fifth-wheel position and load distribution, making it difficult to isolate a pure axle distance effect. Furthermore, semitrailer inertia $I_{p,s}$ is much larger (calculations consistent with reports in the literature indicate values on

the order of $30 \cdot 10^4$ kg m^2) than the tractor inertia $I_{p,t}$ in eq. (6). Thus, the increase in total articulation inertia remains moderate, which explains why the lane-change manoeuvre showed little sensitivity to axle distance.

Our results in Table 1 indicate that axle distance is indeed a factor for the tractor effective yaw moment of inertia about the pivot, in particular for three axle tractors having an axle distance around 4 m. For such a tractor, our calculated effective yaw inertia was about 70 % larger than that of a short 4×2-tractor. These calculations suggest that braking-in-curve and jack-knife susceptibility should be considerably more sensitive to tractor axle distance and configuration than concluded in [2].

5. Conclusions

The influence of axle distance on effective tractor yaw inertia depends strongly on pivot location. If the front axle-to-pivot distance remains fixed, a longer axle distance primarily affects tractor inertia about its center of gravity and the resulting increase in effective yaw inertia is moderate. If the pivot moves rearward, both the tractor center of gravity inertia and the parallel-axis contribution increase, leading to a substantially larger increase in effective yaw inertia. For representative European tractor-semitrailer combinations, the increase in effective tractor yaw inertia may be approximately twice as large when the pivot moves with the axle distance compared to the case of a fixed pivot position. This difference provides a plausible explanation for the varying sensitivity to axle distance observed in the literature, [2,4,6] since different vehicle configurations implicitly adopt different relationships between axle distance and fifth-wheel location.

Disclosure statement

The authors report there are no competing interests to declare.

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