

Steer Laws for Steerable Trailer Axles to Reduce Tire Wear

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ABSTRACT

Majority of the tractor/semi-trailers are equipped with non-steerable solid trailer axles. In low speed cornering maneuvers, the trailer tires scrub in opposite directions, generating unnecessary tire wear. Steerable-axle trailers are beginning to appear in the commercial vehicle market to improve maneuverability and treadwear. In this paper, tire slip characteristics of traditional three-axle trailers in turning maneuvers are investigated analytically. Trailer-axle steer laws, defined as a relation between tractor/trailer articulation angle and trailer axle steer angle, are derived for each trailer configuration. The objective is to minimize tire scrub in low speed turning maneuvers and to generate even treadwear for different wheel positions. Effect of the vehicle forward speed on steer laws is discussed. The steer laws are further evaluated using multi-body vehicle dynamic simulation models. The proposed steer laws are also evaluated for their potential in increasing maneuverability of the articulated vehicles.

INTRODUCTION

Long combination vehicles are equipped with trailer steering systems to improve the low speed maneuverability on narrow winding roads with sharp roundabouts of Australian, Canadian or American road systems ([1] and [2]). Optimization of these steering systems remains the core of research activities in the industry ([3], [4] and [5]) and academia [6]. Although, the use of long combination vehicles in Europe is forbidden, more and more European standard trailers are equipped with steering systems. In addition to their benefits in maneuverability, trailer steering systems offer improved fuel economy and tire treadwear.

In general, three different strategies are used to steer the trailer axles [7]: *self-steering systems*, which rotate the trailer axles in relation to the lateral tire forces, *command-steering systems*, which use the articulation angle to define the axle angles and *pivotal-bogie systems*, which steer in relation to the angle of the bogie assembly. In this paper, only command-steer system is investigated, since it is the most common steering system in Europe. Other configurations are discussed in [8] and [9].

Trailer tires are generally designed to carry vertical load, generate lateral force in corners and to reduce rolling resistance, but not for steering. Application of a steer torque can adversely affect tread wear performance of the trailer tires. As customers do not want to sacrifice load capacity and fuel economy of the trailer tire, they do not prefer steer tires either. Ideal steer laws are presented in this paper, to improve treadwear performance of the trailer tires while maintaining the improved maneuverability of a steering system.

TIRE SCRUB ON NON-STEERABLE TRAILER AXLES IN LOW-SPEED CORNERING

One of the main roles of trailer tires is to carry the vertical load. In non-straight line maneuvers, the tires also need to generate enough lateral force to maintain the trailer on the trajectory. Tire lateral force build-up is different for the left and the right tires due to lateral load transfer. For a rolling tire, the lateral force generates a deformation in the tire footprint. From a more or less square shape in straight driving, the tire's footprint becomes roughly triangular and asymmetric with respect to the footprint center line. The lateral force also results in sideslip angle of the tire. A major part of the tire wear is generated by this footprint distortion and sideslip.

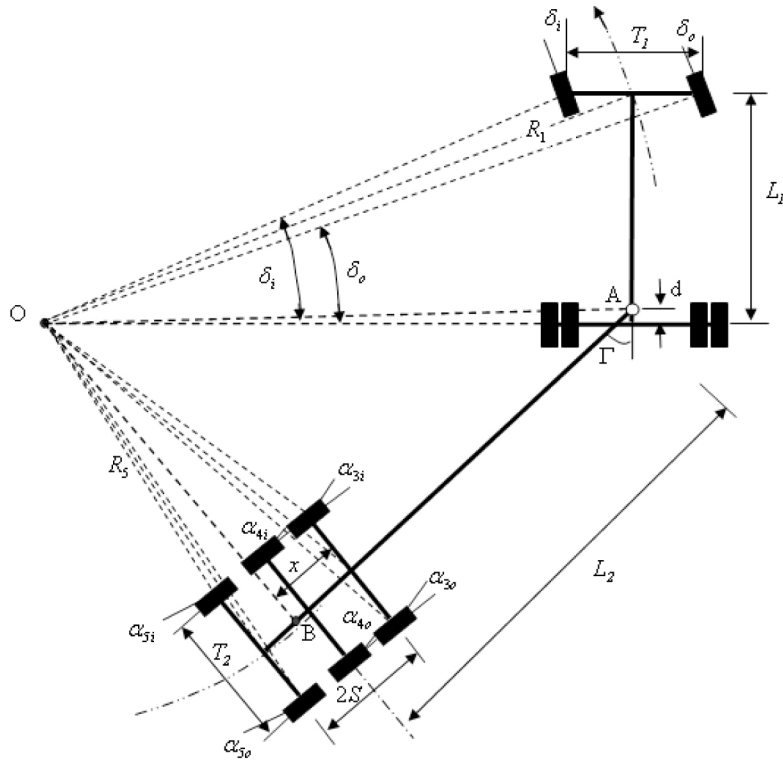


Figure 1. Yaw plane model of EU 5-axle tractor semi-trailer with solid axles.

While the tire slip generated during cornering situations is necessary to maintain the vehicle on its trajectory, tire scrub in parking and low-speed cornering maneuvers generates unnecessary tire wear. To evaluate the amount of tire scrub on standard European tractor semi trailers (4×2-tractor + 3-axle semi-trailer) in low-speed cornering, a simple yaw plane model, illustrated in Figure 1 is used. In low speed cornering maneuvers, effect of inertia forces can be ignored. Assuming no friction on the fifth wheel, even loading conditions and similar tire cornering properties on the trailer axles, tire slip angles on different trailer axles can be derived by applying yaw moment balance around the fifth wheel as follows:

$$\alpha_{3j} = \tan^{-1} \left(\frac{6L_2S + 4S^2}{\sqrt{(6L_1L_2 / \tan \delta_i + 3T_1L_2)^2 - (6L_2^2 + 4S^2) + 36L_2^2d^2 + 3T_2L_2\text{sign}(j)}} \right) \quad (1)$$

$$\alpha_{4j} = \tan^{-1} \left(\frac{4S^2}{\sqrt{(6L_1L_2 / \tan \delta_i + 3T_1L_2)^2 - (6L_2^2 + 4S^2) + 36L_2^2d^2 + 3T_2L_2\text{sign}(j)}} \right) \quad (2)$$

$$\alpha_{5j} = -\tan^{-1} \left(\frac{6L_2S - 4S^2}{\sqrt{(6L_1L_2 / \tan \delta_i + 3T_1L_2)^2 - (6L_2^2 + 4S^2) + 36L_2^2d^2 + 3T_2L_2\text{sign}(j)}} \right) \quad (3)$$

where, $\text{sign}(j) = \begin{cases} -1, & \text{for } j = i \text{ (inside tire)} \\ 1, & \text{for } j = o \text{ (outside tire)} \end{cases}$

L_1 is the tractor wheelbase. L_2 is the distance from the fifth wheel to the center of the trailer axles. d is the fifth wheel offset relative to the tractor rear axle. S is the axle spacing of the trailer axles. T_1 is the wheel spacing of the front axle. δ_i is the steer angle of the inside front wheel. α_{3j} , α_{4j} and α_{5j} are the tire slip angles of the inside tire ($j = i$) and outside tire ($j = o$) on the 3rd, 4th and 5th axles of the combination, respectively.

The turning radius of the tractor (R_1), defined as the distance from the center of the front axle to the turning center, can be written as:

$$R_1 = \sqrt{(L_1 / \tan \delta_i + T_1 / 2)^2 + L_1^2} \quad (4)$$

The turning radius of the center of the rearmost axle (R_5) can be derived as:

$$R_5 = \sqrt{(L_1 / \tan \delta_i + T_1 / 2)^2 + d^2 - L_2^2 - S^2 / 3 - 4S^3 / (3L_2)} \quad (5)$$

The off-tracking of the tractor semi-trailer (ΔD) which is an objective metric to characterize the maneuverability of the vehicle is calculated as:

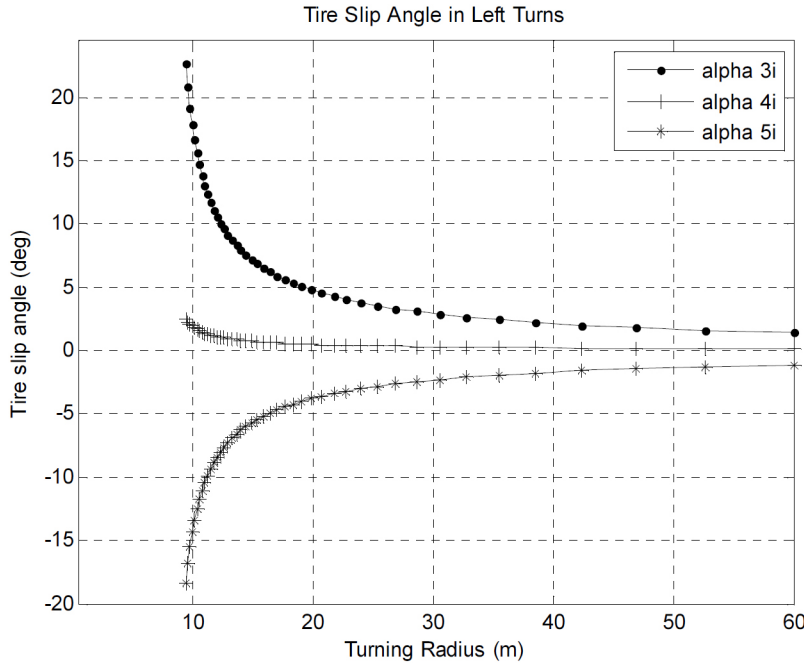


Figure 2. Tire slip angles in left turns (EU 3-axle trailer).

$$\Delta D = R_1 - R_5 \quad (6)$$

For a two-axle tractor towing a three-axle semi-trailer with the following parameters $L_1 = 3.6m$, $T_1 = 2.08m$, $L_2 = 7.4m$, $S = 1.28m$, $T_2 = 2.02m$, $d = 0m$ the relationships between turning radius computed in (4) and tire slip angles expressed in (1), (2) and (3) are shown in Figure 2.

The tire on the 1st trailer axle (alpha 3i) shows positive slip angle (tire lateral force pointing to the right), while the tire on the 3rd trailer axle (alpha 5i) shows negative slip angle (tire lateral force pointing to the left). The tire on the 2nd trailer axle (alpha 4i) has slightly positive slip angle to balance the yaw moment around the fifth wheel. In tight turns, tires on the 1st and 3rd trailer axles scrub in different directions with significantly large slip angles and lateral forces, resulting in fast tire treadwear.

STEER LAWS DEVELOPMENT FOR MINIMIZING TRAILER TIRE SCRUB IN TIGHT TURNS

To reduce unnecessary tire wear in tight turns, one of the options is to steer the trailer wheels. To reduce cost, one of the trailer axles could still be a solid axle, while other two axles are replaced with steerable axles. For a tri-axle semi-trailer, there are a few steer arrangements, as described below.

OPTION I

The first option is to steer the 2nd and 3rd trailer axles, and keep the 1st trailer axle as unsteerable, as shown in Figure 3. In order to have zero sideslip for the trailer tires, the steer angles of the wheels on two rear axles need to be steered to form a common turning center as the front trailer axle. The following relationships between the articulation angle and wheel steer angles can be derived from the geometry arrangement of the tractor semi-trailer:

$$\Gamma = \sin^{-1} \left(\frac{L_2 - S}{\sqrt{(L_1 / \tan \delta_i + T_1 / 2)^2 + d^2}} \right) - \tan^{-1} \left(\frac{d}{L_1 / \tan \delta_i + T_1 / 2} \right) \quad (7)$$

$$\delta_{2j} = \tan^{-1} \left(\frac{S}{(L_1 / \tan \delta_i + T_1 / 2 - d \tan \Gamma) \cos \Gamma + \text{sign}(j) T_2 / 2} \right) \quad (8)$$

$$\delta_{3j} = \tan^{-1} \left(\frac{2S}{(L_1 / \tan \delta_i + T_1 / 2 - d \tan \Gamma) \cos \Gamma + \text{sign}(j) T_2 / 2} \right) \quad (9)$$

$$\Delta D = \sqrt{(L_1 / \tan \delta_i + T_1 / 2)^2 + L_1^2} - \sqrt{(L_1 / \tan \delta_i + T_1 / 2)^2 + d^2 - (L_2 - S)^2 + 4S^2} \quad (10)$$

$$\text{where, } \text{sign}(j) = \begin{cases} -1, & \text{for } j = i \text{ (inside tire)} \\ 1, & \text{for } j = o \text{ (outside tire)} \end{cases}$$