METHOD FOR IMPROVING THE MANEUVERABILITY OF THE STEERING SYSTEM FOR SEMI-TRAILER TRUCKS

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Abstract - To enhance road safety in the vicinity of trucks, a method was suggested to decrease the swept path width of a moving tractor–semi-trailer combination. This study examines the movement of a tractor unit paired with a conventional semi-trailer featuring both fixed axles and steerable wheels through a mathematical approach. Simulation analyses were performed on the two types of trucks. The paper explores the impact of swivel-wheel control on the swept path width of a tractor–semi-trailer equipped with steering wheels. The relevance of swept path width is particularly pronounced in scenarios involving trucks operating within constrained spaces, such as logistics and transshipment center parking lots or urban settings. Although traffic-approved trucks comply with basic homologation standards, minimizing swept path width enhances the tractor–semi-trailer's operational capabilities. Employing the proposed algorithm for steering wheel control offers significant advantages, notably improving road safety and lowering environmental emissions of harmful substances.

Key words - Truck maneuverability; semi-trailer; steered wheels; swept path width.

1. Introduction

Currently, the rapid development of industries has led to an increasing demand for transportation, resulting in a continuous rise in the number of trucks on the road, especially trucks. Trucks are classified based on load capacity, size, and intended use. Among them, the two most common types are conventional trucks and tractor-semitrailer combinations. The biggest disadvantage of conventional trucks is that the cargo bed is usually fixed to the frame, making it difficult to change the type of cargo being transported, especially for bulky or liquid goods. In contrast, tractor-semitrailer combinations are more flexible as they allow the type of cargo to be changed simply by swapping the trailer, while the tractor stays the same, it is capable of transporting various goods. However, the major drawback of this type of truck is its low maneuverability due to its large length, resulting in a large turning radius and wide swept path, especially when turning at sharp corners. This makes tractor-semitrailer combinations face difficulties, and sometimes even impossible to drive on local roads or pass through small roundabouts.

There have been many studies on the dynamics of semi-trailers, each focusing on a different aspect to optimize the performance and stability of the truck. For example, some studies focus on aerodynamic drag, helping to improve fuel efficiency and operational performance [1]. Some systems emphasize agility, directional stability, and rollover mitigation, thereby improving overall truck safety [2]. The angle of articulation between the tractor and the semi-trailer plays a crucial role in the truck's turning agility [3]. In addition, some studies have developed multi-objective stability control algorithms by utilizing differential braking systems, improving control in emergency situations [4]. Methods for lateral stability through additional yaw moment have also been explored to improve truck control on slippery road surfaces [5]. Not only focusing on road movement, but some studies have also proposed intelligent parking support systems for tractor-trailer combinations, helping drivers maneuver trucks in confined spaces [6]. Another important research direction is predicting and detecting instability issues early, allowing drivers to take timely corrective actions to reduce accident risks [7]. Moreover, some studies aim to recover energy from the dynamics of the tractor, contributing to overall performance improvement and reduced fuel consumption [8]. Specifically, for semi-trailers with steerable axles, the dynamic modeling and simulation of such trailers with active steering systems are presented in [9]. The paper in [10] presents a comparative analysis of the performance of different steering mechanisms used in semi-trailers. This study presents the experimental findings of the active steering system applied to tractor–semi-trailer configurations [11]. The method for improving yaw dynamics by controlling the rear wheels forward is discussed in [12]. A robotic tractor-semi-trailer model is presented in [13]. An alternative study investigates an automated approach to designing active steering systems for articulated heavy-duty trucks [14]. However, the studies in [9], [12], and [13] are limited by considering only the single-track dynamic models of articulated trucks and state-space mathematical models, providing a general concept of steering control system operation [14].

This research introduces a generalized methodology for developing a detailed dynamic model of a tractor–semi-trailer equipped with steerable axles and evaluates its simulation results in comparison with those of conventional semi-trailers.

2. Methodology

There exist two main strategies to improve how the truck handles during motion. The first method consists of modifying the wheels' velocity vector directions with respect to the truck's longitudinal axis. The second approach involves modifying the rotational mode of the wheels by utilizing traction and braking forces for the drive axle, or solely applying braking forces to the passive axle. Additionally, these methods can be combined, as found in [15].

An active steering system consists of the following components: input parameters, control mechanism, control algorithm, and power source.

Input parameters play a crucial role in providing data for the active steering control system. There are two approaches to determine the input parameters for the system: (1) The first approach utilizes the tractor's steering angle as the input parameter. These parameters are collected through sensors placed in the tractor's steering mechanism. Using this approach positively impacts the truck's ability to turn in place, as there is no deviation angle between the tractor and the trailer, allowing the truck to turn with the least amount of space. However, if the steering angle of the tractor is opposite to the deviation angle of the truck combination, the overall trajectory of the truck becomes difficult to predict because it does not accurately reflect the true kinematic state of the entire truck combination. This causes instability, making effective control possible only when the tractor's steering angle is zero. (2) The second method involves using the offset angle between the tractor's and the semi-trailer's longitudinal axes as an input parameter. These parameters are collected through sensors placed at the hitch point (the connection between the tractor and the trailer). This approach accurately reflects the actual geometric relationship between the two parts of the truck combination, making it particularly suitable for situations where there is a bending angle between the tractor and the trailer. Thus, in this paper, the input parameter based on the deviation angle between the tractor's longitudinal axis and the semi-trailer's longitudinal axis is regarded as the optimal choice.

Actuating Element:

Figure 1 illustrates the steering control methods for the tractor based on the deviation angle between its longitudinal axis and that of the semi-trailer. The rotation of a system in Figure 1(a) or a combined variant in Figure 1(c) increases the height of the cargo floor of the semi-trailer due to the steering mechanism with a rotating structure beneath the trailer's frame. Additionally, the swept path also increases significantly during the turning process of the semi-trailer, but this steering mechanism does not limit the width of the trailer's frame. Rotating the axle in Figure 1(b) requires narrowing the frame's width, which raises the height of the cargo floor. However, the most significant drawback of both systems is the kinematic mismatch in wheel movement, meaning the lateral slipping of the wheels cannot be completely eliminated during the truck's turning. Moreover, the increase in truck height due to the steering mechanism beneath the frame raises the truck's center of gravity, leading to instability, especially when turning sharp corners, increasing the risk of tipping and compromising safety during operation. The method in Figure 1(d), using a steering trapezoid, addresses these issues. Therefore, this method is applied in this study to improve the maneuverability of the tractor.

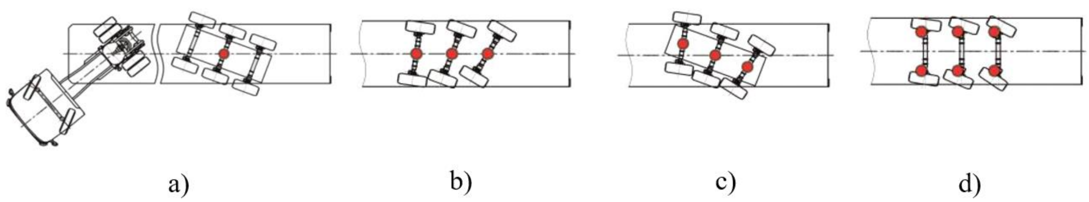

Figure 1. *Types of Transmission Components for Organizing the trailed unit's turn control system [16]*

Power source:

The power source can be mechanical, hydraulic, pneumatic, electrical, or a combination of these. Each type of power source has its own advantages and limitations: Mechanical drive systems have a simple structure, are easy to fabricate and maintain, and provide quick feedback. However, they are difficult to control precisely, require high control forces, and are significantly affected by slack and wear in the mechanical system. Hydraulic drive systems provide high transmission force and relatively accurate control of force and position, making them suitable for systems that require high torque. The drawbacks include system complexity, leakage issues, high maintenance costs, and sensitivity to environmental conditions. Pneumatic drive systems are simple, inexpensive, safe, and provide quick feedback. However, their efficiency is low due to energy loss during compression. Electric drives allow precise control, are easy to integrate with automated control systems, and require little maintenance. However, they have limited torque, are less effective in harsh environments, and have high maintenance and repair costs. Hybrid drives (such as electric-hydraulic or electric-pneumatic) combine the advantages of each system, providing flexibility and high performance. However, they have complex structures, high costs, and require advanced control techniques. Considering the need for model simplification and feasibility in current conditions, choosing pneumatic drive is reasonable.

3. System model

Figure 2 illustrates the stable turning trajectories of two truck configurations: the tractor connected to a conventional semi-trailer as shown in Figure 2a, and the tractor connected to a semi-trailer with steering capabilities as shown in Figure 2b. In both cases, the steering angle of the tractor is kept the same, so the tractor portion of the truck follows the same trajectory, resulting in the same turning radius for the tractor. Once the motion trajectory of the tractor is defined, the outer turning radius may be determined as the spacing from the center of rotation, O, to point A, which represents the outermost point on the tractor. Assuming the center of rotation of the semi-trailer coincides with that of the tractor, when the trailer wheels are properly steered, a steering angle may be established such that the outermost point of the semi-trailer (point B) will follow the same path as point A. Steering the semi-trailer helps minimize the deviation angle between the longitudinal axes of the tractor and the semi-trailer, thereby reducing the inner turning radius of the semi-trailer. This results in a significant reduction in the overall turning path of the entire truck combination.

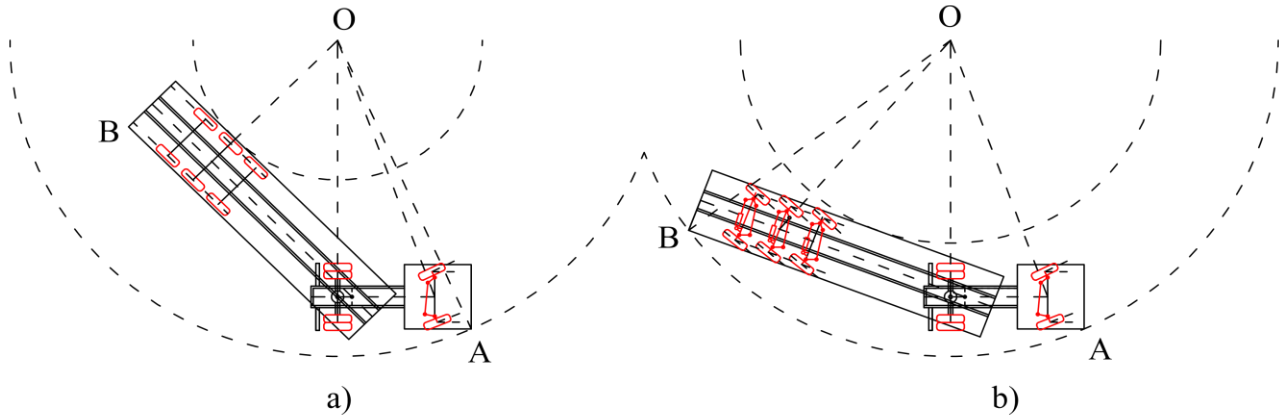

***Figure 2**. Turning of a Conventional Combined Truck (a) and a Combined Truck with a Steering Axle Trailer (b)*

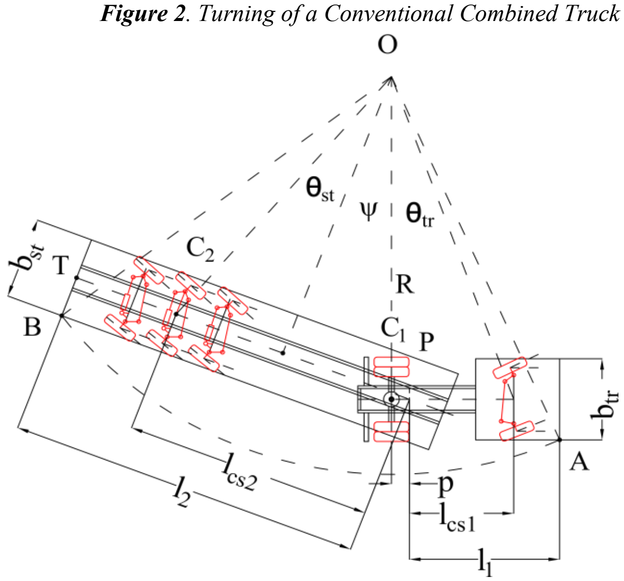

***Figure 3.** Overview of the Tractor and Semi-Trailer Combination*

3.1. Analysis

For the analysis, a two-axle tractor and a three-axle semi-trailer were used. To simplify the model, the shapes of both the tractor and the semi-trailer were approximated as rectangles. It is assumed that the steering angles of the wheels on the same axle (for both the tractor and the semi-trailer) are identical. The dimensions of the tractor and semi-trailer are shown in Figure 3. In this context, the parameters are defined as follows: l_{cs1} represents the wheelbase of the tractor; l_1 is the distance from the rear axle of the tractor to the front of the tractor, p refers to the distance from the rear axle of the tractor to the center of the hitch, b_{tr} is the width of the tractor, l_2 is the distance from the rear of the semi-trailer to the center of the hitch, l_{cs2} is the distance from the center axle of the semi-trailer to the center of the hitch, and b_{st} indicates the width of the semi-trailer.

The motion of the tractor and semi-trailer is analyzed within a horizontal plane. *A* coordinate system is defined with its origin located at point *O*, representing the center of rotation of the tractor, as illustrated in Figure 4. In this coordinate system, the longitudinal axis of the tractor is aligned with the x-axis. The key reference points are denoted as follows:

O: the central rotation point of the tractor and semi-trailer system,

C_1: the position of the tractor's rear axle,

P: the hitch connection point between the tractor and the semi-trailer,

A: the farthest point on the tractor's trajectory,

C: the location of the middle axle of the semi-trailer,

B: the outermost point on the semi-trailer's trajectory.

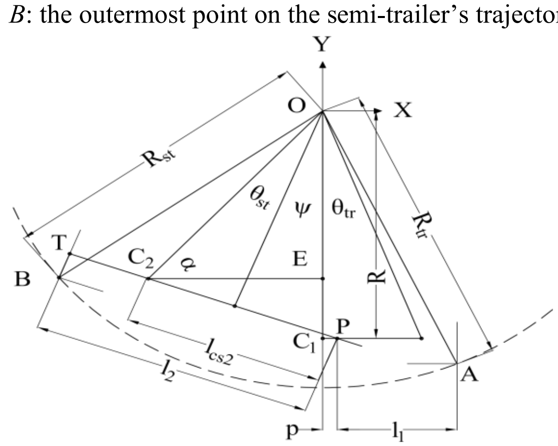

***Figure 4.** Basic markings and dimensions of the tractor and the semi-trailer*

As shown in Figure 4, during steady-state cornering, the front wheels of the tractor are steered by an angle θ_{tr}, while the rear wheels of the semi-trailer are steered at an angle θ_{st}. The orientation difference between the tractor's and semi-trailer's longitudinal axes is denoted by Ψ. Given that the truck is maneuvering at a low speed, the slip angles of the individual wheels are assumed to be negligible.

The turning radius of the tractor is the distance from the center of rotation O to the center of the rear axle of the tractor:

$$R = \frac{l_{cs1}}{\tan\theta_{tr}} \quad (1)$$

The outer turning radius of the tractor is:

$$R_{tr} = \sqrt{(R+\frac{1}{2}b_{tr})^2 + l_1^2} \quad (2)$$

The position of point T is determined as follows:

$$x_T = p - l_2.\cos\psi \quad (3)$$

$$y_T = R - l_2.\sin\psi \quad (4)$$

The position of point B is determined as follows:

$$x_B = x_T - \frac{1}{2}.b_{st}.\sin\psi \quad (5)$$

$$y_B = y_T - \frac{1}{2}.b_{st}.\cos\psi \quad (7)$$

The outer turning radius of the semi-trailer is:

$$R_{st} = \sqrt{x_B^2 + y_B^2} \quad (8)$$

The angle Ψ, which ensures that both the tractor and the semi-trailer share an identical outer turning radius, satisfies the following equation:

$$R_{tr} = R_{st} \quad (9)$$

The optimal steering angle of the semi-trailer wheels is determined from the geometric relationships shown in Figure 4. Considering the triangle OKE, we have:

$$\tan\alpha = \frac{OE}{C_2E} = \frac{R - l_{cs2}\cos\psi}{l_{cs2}\sin\psi - p} \quad (10)$$

and $\psi + \alpha + \theta_{st} = 90^o \Rightarrow \theta_{st} = 90^o - \psi - \alpha$

lead to:

$$\theta_{st} = 90^0 - arctg(\frac{R - l_{cs2}.\sin\psi}{l_{cs2}.\cos\psi - p}) - \psi \quad (11)$$

Since the steering angle of the semi-trailer wheels is opposite to the bending angle of the truck, therefore:

$$\theta_{st} = arctg(\frac{l_{cs2}.\sin\psi - R}{p - l_{cs2}.\cos\psi}) + \psi - 90^0 \quad (12)$$

3.2. Assumptions Used for the Calculations

The reference simulation data were taken from the FAW tractor model CA4160P7K2E5, as follows:

- Tractor dimensions: l_{cs1} = 3.4m; b_{tr} = 2.5m; l_1 = 4m; p = 0.5m.

- Semi-trailer dimensions: l_2 = 13.19m; b_{st} = 2.5m; l_{cs2} = 9.81m.

4. Results and Discussion

The diagrams provided illustrate two relationships: one between the tractor's steering angle and the combination truck's steering angle as in Figure 5, and the other between the tractor's steering angle and the semi-trailer's optimal steering angle as in Figure 6.

Figure 7 highlights the disparity in turning radius between a standard semi-trailer (without a steering axle) and one whose wheels turn according to the specified algorithm. This difference becomes particularly noticeable at greater tractor steering angles, such as those exceeding roughly 8–10°. It is essential to observe that when maneuvering a combination truck equipped with a semi-trailer lacking turning wheels, the steering angle of the truck is constrained by its geometric design. Based on the given example, a maximum tractor steering angle of approximately 19.5° is achievable under such conditions. In this case, the semi-trailer axle revolves around its own center. However, this scenario is purely theoretical, as the truck's steering angle is additionally restricted by the requirement to avoid collisions between the semi-trailer and the tractor's cab.

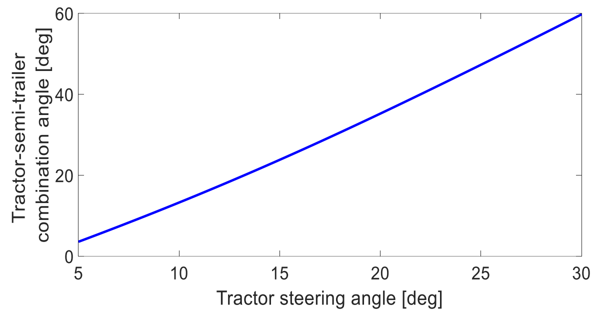

Figure 5. *Relationship between the steering angle of the tractor and the overall steering angle of the articulated truck*

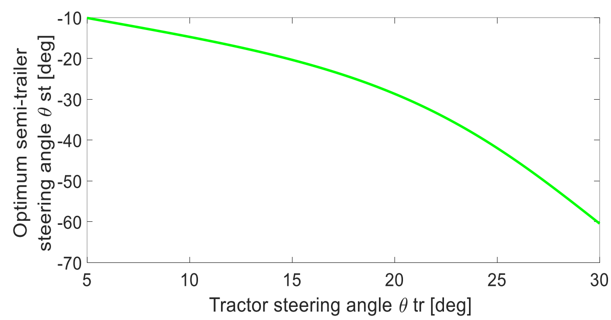

Figure 6. *Functional relationship between the tractor's steering input and the calculated optimal steering angle for the semi-trailer under coordinated maneuvering*

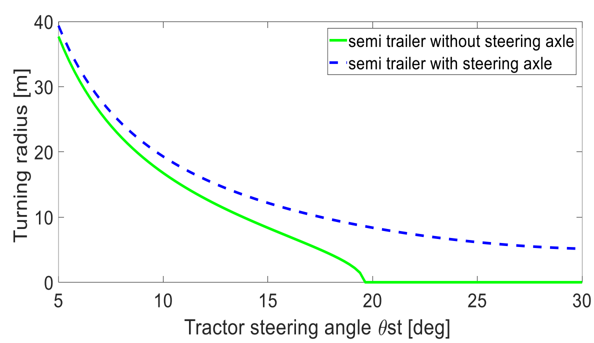

Figure 7. *Comparison of turning radius between a semi-trailer equipped with a steered axle and one with a fixed axle*

The purpose of optimizing the steering mechanism for semi-trailers is to achieve an external turning radius for the semi-trailer that matches that of the tractor unit. When the tractor is steered at a specific angle, its path forms a circular trajectory with a fixed center and a constant radius.

The outermost point of a semi-trailer follows a distinct trajectory during cornering. For standard semi-trailers with non-steered, rigid axles, this point typically deviates from the path traced by the corresponding point on the tractor. In most cases, the semi-trailer's turning path exhibits a smaller radius than that of the tractor, resulting in a significantly wider swept path for the entire articulated truck. This discrepancy can lead to a considerable increase in the lateral clearance required, compared to a standalone truck or tractor. The issue becomes especially critical in tight turns or confined environments, where the front outer corner of the semi-trailer may swing outward beyond the intended truck envelope-creating a potential safety risk for surrounding obstacles or road users.

In conventional articulated trucks lacking steering axles on the semi-trailer, it is crucial to ensure sufficient clearance between the tractor’s cab and the front face of the semi-trailer. Inadequate spacing may result in contact between the semi-trailer’s front corner and structural elements of the tractor during turning. By incorporating steerable axles on the semi-trailer, the articulation angle-defined as the angle between the longitudinal axes of the tractor and trailer-can be significantly reduced during cornering. This reduced angular deflection enables a shorter gap between the tractor cab and the trailer’s front wall, which in turn allows for a longer front overhang on the trailer. Consequently, this configuration not only increases the available cargo volume but also improves the aerodynamic profile of the truck combination, reducing overall drag.

5. Conclusion

Equipping semi-trailers with steering axles significantly reduces the swept path width during turning maneuvers. This design feature also limits the maximum articulation angle between the semi-trailer and the tractor’s longitudinal axis, which permits a tighter coupling distance between the trailer and the cab. As a result, the semi-trailer’s available cargo space can be expanded. Furthermore, integrating a steering control algorithm enables the use of longer tractor–trailer configurations while remaining within maneuverability limits. Reducing the spacing between the cab and trailer not only optimizes space utilization but also improves aerodynamic performance-leading to better fuel economy and lower emissions.

Integrating a steerable axle into a truck semi-trailer, though significantly more complex and costly than traditional designs, offers notable advantages. It enhances the tractor–semi-trailer’s traction performance and boosts its operational safety in scenarios where a standard truck combination may be limited due to its physical dimensions. In the next study, the authors focused on dynamic analysis and system testing on a laboratory model.

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