

Handling Comparison of Vehicles with Steerable Auxiliary Axles

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ABSTRACT

Self-steered or caster steered axles are commonly used to support load on multi-axle commercial vehicles. Such axles can allow more payload to be hauled in some vehicle configurations under the existing bridge formulas. These self-steered axles cannot generate a side load, and serve to unload surrounding fixed axles that do generate lateral forces to turn the vehicle with payload. Since the tire's ability to generate a side load is dependent upon its load, the use of caster-steered auxiliary axles can upset the balance (or the understeering) properties of the vehicle. This work will define the effect of adding a caster steered auxiliary axle and compare it with a steerable axle that positively controls the steer angle and thereby generates a lateral force. This work assumes the reader has a basic knowledge of the well publicized "bicycle" model, and particularly its extension to multi-axle vehicles.

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INTRODUCTION

Multi-axle commercial vehicle handling continues to be of great interest as roadway congestion and energy costs are drivers of increased vehicle mass, while concern for roadway damage demands longer wheelbases and multiple axles on these larger vehicles that must be driven safely on existing roadways by operators of varying experience. Steering a rear axle of a three-axle vehicle can improve handling by reducing the turning radius associated with a given steering input. With rear axle steer there can be a greater distance between axles while handling remains more predictable.

Characterization of vehicle handling was first performed on two-axle passenger cars. It has been long appreciated that for vehicles traveling at a relatively constant forward speed with lateral accelerations limited to correspond to the linear range of the tires, a simple model including yaw and lateral velocity degrees of freedom can be used to predict vehicle handling performance. Because such a model neglects sprung mass roll, the action of linear tires on a common axle can be combined, with the result referred to for obvious reasons as the "bicycle model," and its parsimonious combination of simplicity and ability to characterize well known vehicle properties have resulted in its wide use [1, 2, 3, 4]. The assumptions inherent in the bicycle model render it perhaps even more applicable to commercial vehicles that tend to

travel at constant speeds with low lateral accelerations. Many of the vehicle handling properties are seen to be functions of the vehicle wheelbase and understeer.

The two-axle bicycle model has been extended to vehicles with arbitrary axle configurations [5, 6]. The equivalent wheelbase and understeer parameters can directly calculated for vehicles with any number of axles, any of which can be steered. Furthermore the dynamic model of such vehicles can be directly written without appeal to summation of forces and moments.

Ellis [7] recommended a method of equating the action of a tandem axle bogie to an equivalent single axle acting midway between the tandem spread. If it is assumed that load is equally shared between the tandem axles and all tires have the same cornering stiffness this method results in a simple augmentation adding a yaw resisting moment to existing two-axle models. Winkler and Gillespie [8] developed a more general steady-state handling model for a three-axle vehicle. Just as the present work, Winkler and Gillespie's is restricted to the common vehicle configuration of a single steered axle in the front and a tandem driven axle combination in the rear. It has been shown that the methods of Ellis, Winkler and Gillespie, and the generalized method used in this work yield equivalent results for similar three-axle vehicles [9].

There are several methods of steering the rear axles of three-axle vehicles. One general way is to positively control

the position of the steered wheels on the rear axle based on measurements such as handwheel displacement and vehicle speed. It has been shown that steering the rearmost axle proportionally to the front steering input can reduce the equivalent wheelbase of the vehicle [10] and decrease tire wear [11].

A second general way of steering an auxiliary axle is to allow it to self-steer. Wheels on such a self-steered or caster-steered axle will rotate to minimize the lateral force generated by the tire. Such self-steered axles will demonstrate the same low-speed performance advantages seen in the positively controlled axles, but cannot generate a lateral force.

This paper will compare the various methods of steering auxiliary axles and report their effect on overall vehicle handling in terms of the understeer and equivalent wheelbase parameters that combine to describe steady state handling.

VEHICLE MODEL

The much celebrated two-degree-of-freedom or yaw plane model has received extensive coverage in the literature. Results from the literature are modified.

Handling Model from Literature

A generalized two-degree-of-freedom (bicycle) model developed for vehicles of arbitrary complexity is used in this work [5, 6]. For brevity the results are used directly in this work, and the reader interested in their derivation should consult the references. In general side force F_i generated by a tires are functions of the difference between the direction a tire is pointing and the direction it is moving, or the slip angle α_i .

$$F_i = C_i \alpha_i$$

Equation 1

Because all tires on the same axle see approximately the same slip angle their action can be combined. Lateral forces and yaw moments can be summed to produce a two-degree-of-freedom model of vehicle handling. These two equations of motion can be simultaneously solved for a steady-state solution [5,6]

Steady-state handling of a vehicle is fundamentally a property of the yaw rate in response to a handwheel steering input.

$$\frac{r}{\delta} = \frac{u}{l_n + u^2 K_n}$$

Equation 2

where r is the yaw rate of the vehicle and u is its longitudinal velocity. The steering input measured at the front wheel is δ and can be related to the handwheel input by the steering ratio. For the arbitrary n -axle vehicle the equivalent wheelbase is l_n and understeer is K_n . As seen in Equation 2 a vehicle is said to be understeering if the yaw rate response decreases at high speed. Depending upon vehicle parameters K_n can be negative in which case the vehicle is said to oversteer, and the yaw rate response increases at high speed.

This is a situation that demands driver skill, and should be avoided when possible.

For a general vehicle these equivalent wheelbase and understeer parameters have been derived [5,6],

$$l_n = \frac{(\sum_{i=1}^n C_i)(\sum_{i=1}^n x_i^2 C_i) - (\sum_{i=1}^n x_i C_i)^2}{\sum_{i=1}^n \eta_i C_i (\sum_{j=1}^n (x_i - x_j))}$$

Equation 3

$$K_n = \frac{-m \sum_{i=1}^n x_i C_i}{\sum_{i=1}^n \eta_i C_i (\sum_{j=1}^n C_j (x_i - x_j))}$$

Equation 4

where η_i is the constant of proportionality (or "gain") between the displacement of the i th axle and the primary steered front axle. If the i th axle is not steered η_i is zero.

The x_i in Equation 3 and Equation 4 are the signed locations of the n axles. An axle in front of the vehicle center of mass has positive location, and if the axle is behind the center of mass it will have a negative location. In this work we focus on the three-axle vehicle in its most common configuration of a single primary steered axle at the front, and two closely coupled tandem axles at the rear, as shown in Figure 1.

The fundamental forces that determine a vehicle's handling response are generated by the tires. A tire generates a lateral force in response to a slip angle, that is the difference between the direction the tire is pointed and the direction it is moving. As shown in Fig 2, the direction a given tire is moving is a function of the vehicle's longitudinal and lateral velocities, and of its yaw rate. The side force coefficient C_i found in Equation 3 and Equation 4 multiplies the slip angle of a tire to yield its lateral force.

In the two-degree-of-freedom model all tires experience the same slip angles, so their action can be combined for an overall effect at each axle. By summing forces and moments and considerable mathematical manipulation Equation 2, Equation 3 and Equation 4 are derived [5,6]. Special cases of Equation 3 and Equation 4 can be written for the three-axle vehicle of Figure 1.

$$l_3 = \frac{C_1 C_2 (l - t)^2 + C_1 C_3 l^2 + C_2 C_3 t^2}{C_1 C_2 (l - t) + C_1 C_3 l}$$

Equation 5

$$K_3 = \frac{-m(x_1 C_1 + x_2 C_2 + x_3 C_3)}{C_1 C_2 (l - t) + C_1 C_3 l}$$

Equation 6

where l is the overall wheelbase

$$l = x_1 - x_2$$

Equation 7

and t is the tandem spread between the rear axle.

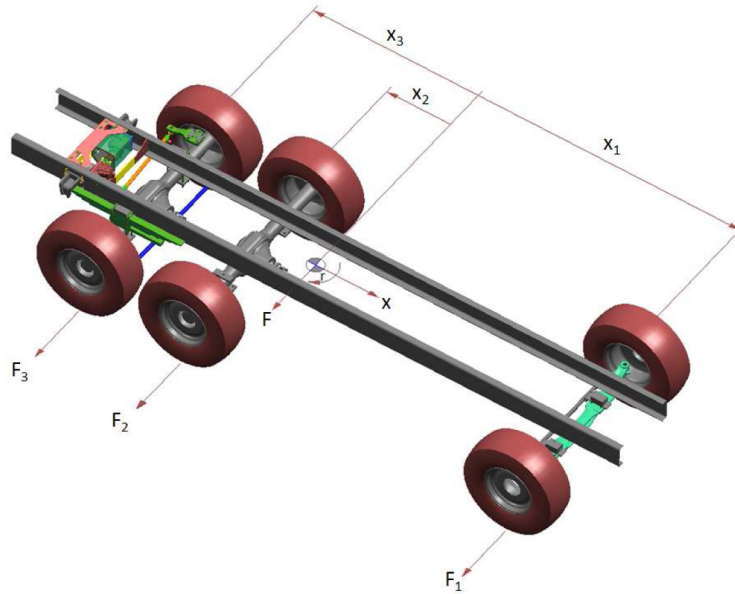


Figure 1. A typical three-axle vehicle with tandem rear axles.

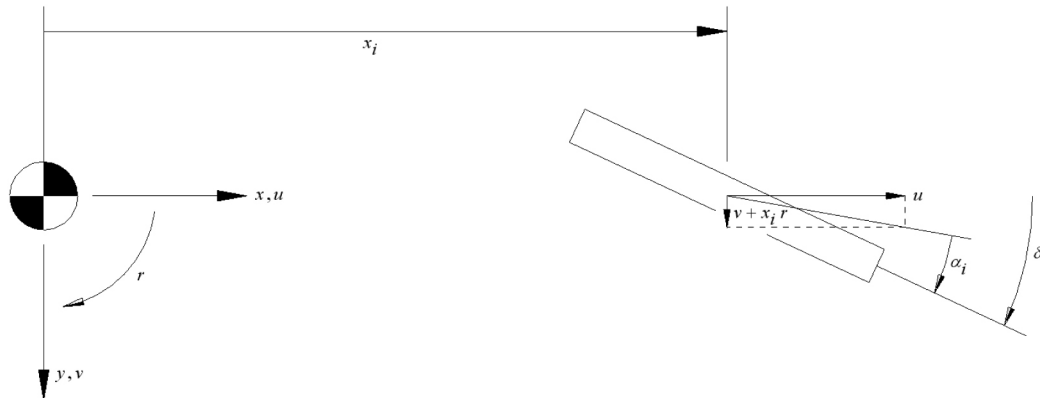


Figure 2. Slip angle of a tire in terms of vehicle parameters

$$t = x_2 - x_3$$

Equation 8

Modification for Normal Force

The typical two-degree-of-freedom vehicle model assumes a proportional relationship between the slip angle of a tire and the lateral force it generates. For small slip angles and relatively constant vertical loads on the tire this is a good assumption. This assumption does not allow analysis of a caster-steered axle, however. The characterization of lateral force produced by a tire can be quite complicated [12] but for the purposes of this work a simple tire model can be used,

$$C_i = C_{i,o} \frac{N_i}{N_o}$$

Equation 9

where the side force coefficient C_i of each axle i is a function of the nominal side force coefficient corresponding to a

nominal normal load N_o , and the actual normal load carried by that axle N_i . This model is consistent with representative data from a commercial vehicle manufacturer [5].

When Equation 9 is inserted into Equation 5 and Equation 6 the results are the handling parameters for a vehicle with varying axle loads.

$$l_3 = \frac{C_{1,o}N_1C_{2,o}N_2(l-t)^2 + C_{1,o}N_1C_{3,o}N_3l^2 + C_{2,o}N_2C_{3,o}N_3t^2}{C_{1,o}N_1C_{2,o}N_2(l-t) + C_{1,o}N_1C_{3,o}N_3l}$$

Equation 10

$$K_3 = \frac{-mN_o(x_1C_{1,o}N_1 + x_2C_{2,o}N_2 + x_3C_{3,o}N_3)}{C_{1,o}C_{2,o}N_1N_2(l-t) + C_{1,o}C_{3,o}N_1N_3l}$$

Equation 11

The axle locations in Equation 11 are functions of the normal loads on each axle,