

Tire Wear Improvement by Steering a Third Axle

2011-01-2148

Published
09/13/2011Daniel Williams
TRW Commercial Steering Systems

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doi:10.4271/2011-01-2148

ABSTRACT

The conventional rear tandem axle of a three-axle vehicle produces a yaw resisting moment that adversely impacts vehicle performance. This work examines the effect of steering the rear axle on tire wear. Using actual vehicle test data, a tire wear model is developed. This tire wear model is then used to predict tire wear savings over an actual commercial vehicle duty cycle when the rear axle is steered. The result of this projection is shown to be consistent with reported third party field experience.

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 the third 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.

Ellis [5] 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 [6] 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.

Winkler [7] has presented the most comprehensive work on steady state turning of multi-axle vehicles, using Pacejka's [8] handling diagram methodology.

The dynamic equations of motion corresponding to a three-axle vehicle provide a steady state solution that yields characterization of handling. Just as wheelbase and understeer can be used to describe steady-state handling characteristics of two-axle vehicles, their equivalents can be determined for three-axle vehicles [9]. Derived notions of understeer and effective wheelbase for a three-axle vehicle are augmented with a rear steering input that is proportional to the front steering angle, thereby forming a new single-input linear model [10]. In an intuitively satisfying result, this simple rear axle steering strategy results in the vehicle effectively turning about the rigid second axle. This configuration is an idealized version of third axle steering systems currently available in Europe.



Figure 1. Multi-Axle Test Vehicle (parameters in [Appendix](#))

Tire wear can be measured for a three axle-axle vehicle in a steady state turning condition [11]. Ellis speculates tire wear is proportional to the square of the slip angle [5]. Later, Miller et. al. report that the exponential relationship between tire wear and slip angle can vary from between the 2nd and 4th power [12]. The present work uses measured tire wear to determine parameters for an exponential relationship between slip angle and tire wear rate. The model is then applied to an actual urban drive cycle to predict tire wear for a three-axle vehicle with and without rear axle steering.

A trailer manufacturer reports that steering rear trailer axles results in three times longer tire life in a duty cycle that is 80% urban and 20% highway [13]. Specifically, the trailer tires lasted 40,000 km in a standard installation, and 120,000 when steered. Tires on a trailer application will experience braking forces in addition to lateral force. These braking forces will be dependant upon the vehicle state trajectory, and roughly independent of an axle being steered or not steered. Such longitudinal forces not considered in this work will combine with the lateral forces considered below to cause tire wear in a more complicated manner.

VEHICLE TESTING AND PERFORMANCE ANALYSIS

The effect of steering the rear axle of a three-axle vehicle on tire wear can be determined experimentally. The steady state handling properties of a three-axle vehicle can be expressed in terms of an equivalent wheelbase l_e and equivalent understeer, K_e [10],

$$\delta_1 = \frac{l_e}{R} + urK_e$$

Equation 1

where δ_1 is the front axle steering input, R is the radius of the steady state turn, and u and r vehicle speed and yaw rate respectively. Using

$$r = \frac{u}{R}$$

Equation 2

in general,

$$\delta_1 R = l_e + K_e u^2$$

Equation 3

At low speed the equivalent wheelbase of a vehicle is equal to the product of the steering input and the resulting radius of curvature of the vehicle turning in steady state. This observation agrees well with Winkler's geometric determination of equivalent wheelbase [7]. As vehicle speed increases there is a dynamic component to the steady state yaw balance that determines the equivalent understeer.

Knowing the left hand side of [Equation 3](#) directly, or by inference using [Equation 2](#) and measured vehicle data, a multiple regression analysis can be performed to establish parameter values for l_e and K_e on any data set collected under reasonably steady-state conditions.

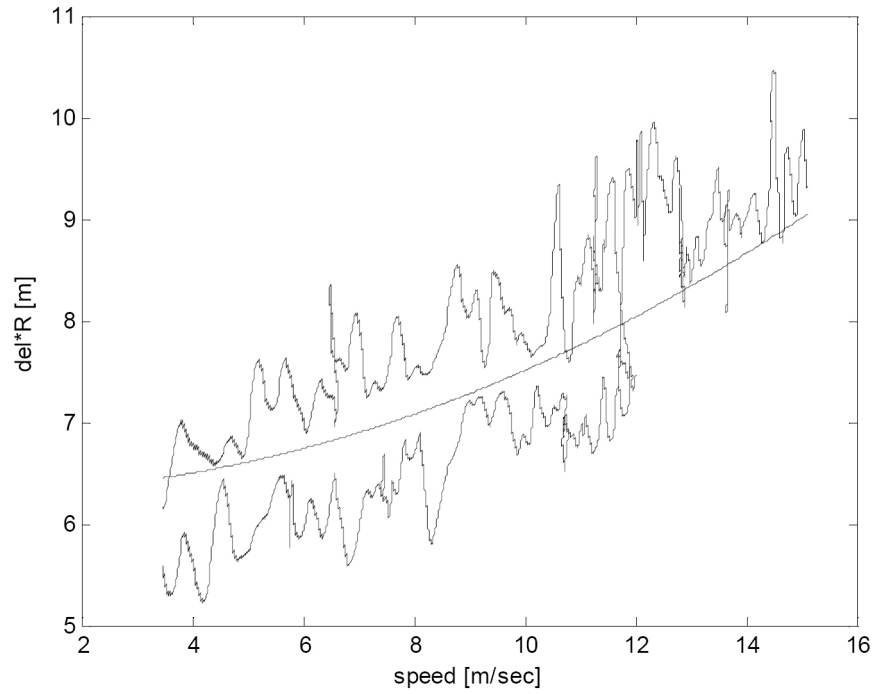


Figure 2. Modeled and Measured Vehicle Handling, Rear Axle Centered

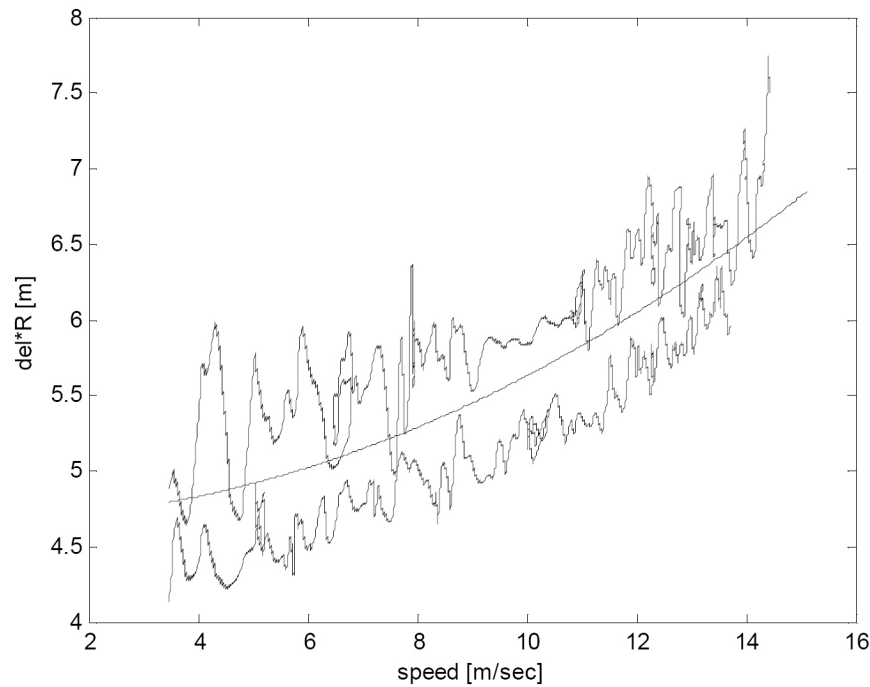


Figure 3. Modeled and Measured Vehicle Handling, Rear Axle Active

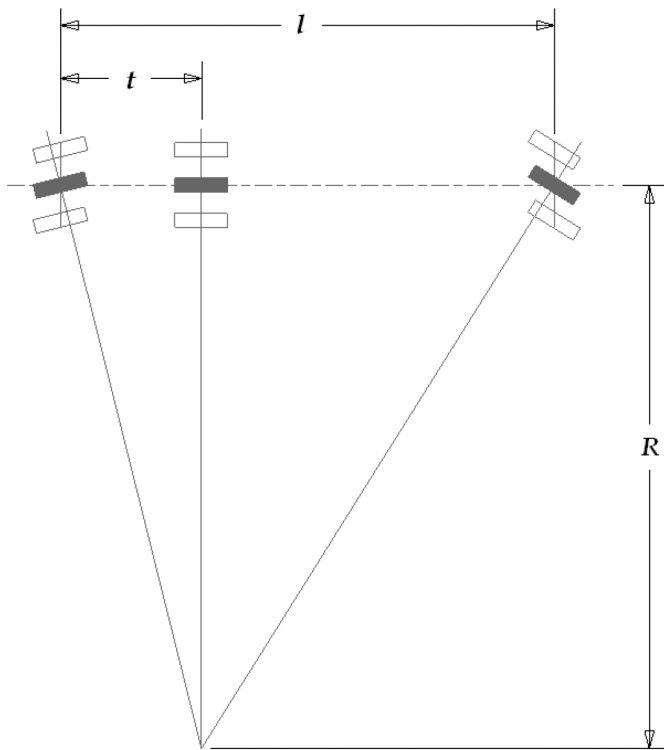


Figure 4. Rear Steering About a Point.

In this particular case a vehicle was driven at slowly increasing forward speeds on a spacious relatively flat concrete surface with a constant steering input. The vehicle used is shown in [Figure 1](#) (the apparent second axle is a

caster steered “lift axle” that was not engaged for this test). The vehicle was driven around a large radius at slowly increasing speed in clockwise and counterclockwise directions. From the data collected the product $\delta_1 R$ was calculated for a vehicle with the rear axle centered as shown in [Figure 2](#).

This vehicle was equipped with an electronically controlled steerable rear axle using a simple control law steering the rear wheels δ_3 as a constant proportion of the front steering input.

$$\delta_3 = \eta \delta_1$$

Equation 4

A simple relationship can be formed based on their respective distances from the second (unsteered) axle [11],

$$\eta = \left(\frac{-t}{l-t} \right)$$

Equation 5

where l is the length between the first and third axles, and t is then tandem spread distance between the second and third axles.

In this manner, as shown in [Figure 4](#) the vehicle effectively turns about a point colinear with the extended second axle defined by its intersection with perpendiculars from the front and rear wheels.

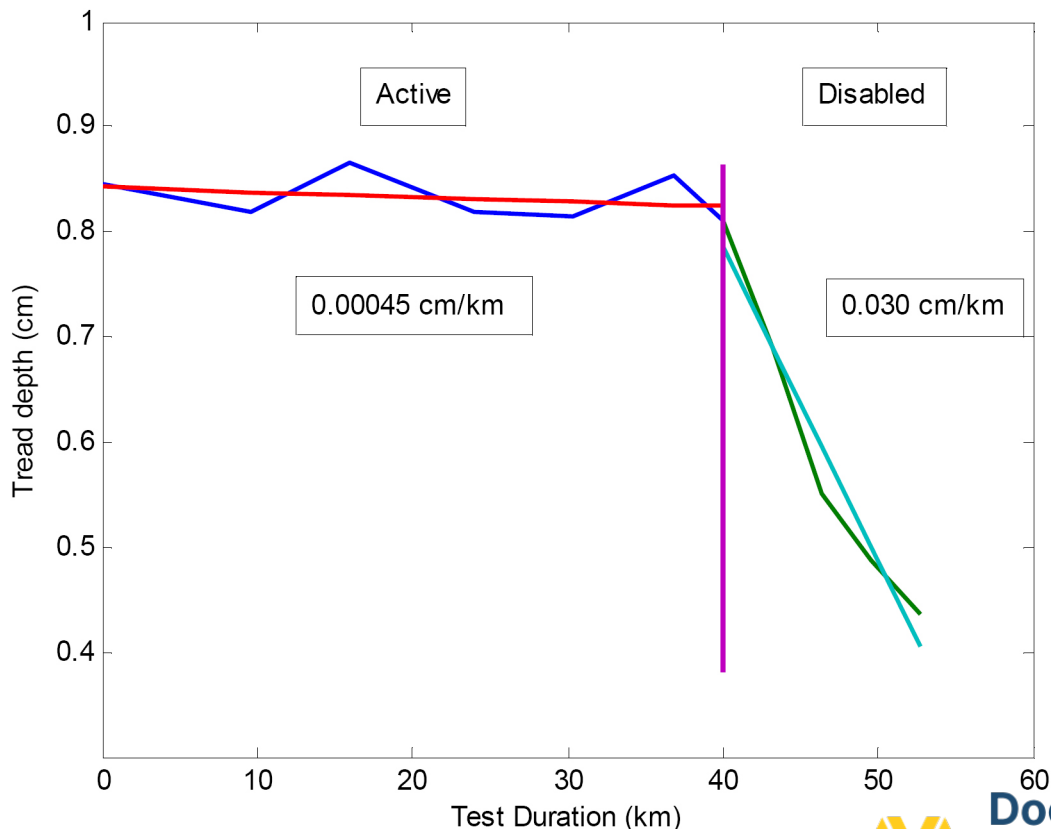


Figure 5. Rates of Tire Wear for Steered and Unsteered Rear Axle [11]