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Research Article

Handling Stability of Tractor Semitrailer Based on Handling Diagram

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Handling instability is a serious threat to driving safety. In order to analyze the handling stability of a tractor semitrailer, a handling diagram can be used. In our research, considering the impact of multiple nonsteering rear axles and nonlinear characteristics of tires on vehicle handling stability, the handling equations are developed for description of stability of tractor semi-trailer. Then we obtain handling diagrams so as to study the influence of driving speed, loaded mass, and fifth wheel lead on vehicle handling stability. The analysis results show that the handling stability of a tractor semi-trailer when the tractor has two nonsteering rear axles is better than that when the tractor has only one nonsteering rear axle. While the stability in the former case is slightly influenced by driving speed and loaded mass, the latter is strongly influenced by both. The fifth wheel lead is found to only slightly influence handling stability for both tractor semi-trailers. Therefore, to ensure the driving safety of tractor semi-trailers when the tractor has only one nonsteering rear axle, much stricter restraints should be imposed on driving speed, and the loaded mass must not exceed the rated load of the trailer.

1. Introduction

Tractor semitrailers make up a large proportion of road transport vehicles due to their high transportation efficiency and economy. In 2010, the number of lorries in China reached 17 million, of which 8.7% were tractor semitrailers, and the number is growing at a rate of 20% per year.

At the same time, the number of traffic accidents involving tractor semitrailers remains high, and these accidents often cause serious personal injuries and property damage. Chinese statistics show that more than 1 in 3 tractors caused an accident on the highway in 2010, leaving 10,881 people dead.

Steering instability is one of the main contributors to traffic accidents involving tractor semitrailers. But, until now, little attention has been paid to it, and there are relatively few works on the topic [1–3]. This makes such a study essential.

Two different approaches are generally used to analyze vehicle handling stability: open and closed loop measurements. Unlike the former, the latter does not reflect the vehicle's inherent stability because driver behavior is taken into consideration [4–6]. As a result, most scholars prefer to use open loop analysis.

There are many methods of analyzing the open loop handling stability of vehicles, including (among others) dynamic theory [4–10] and graphical representations [11–13]. One of the most useful methods is the handling diagram invented by Pacejka [14–16], which has been used extensively due to its intuitive approach and convenience [11, 12, 17–22]. In [11, 12, 17, 18], handling diagrams were used to describe a general vehicle's handling stability based on linear or nonlinear models of vehicle dynamics. In [19–21], the handling stability of special vehicles, such as heavy trucks and multiwheel combat vehicles, was analyzed using handling diagrams. As a result, compared to dynamic theory, handling diagrams are easy to obtain and comprehensively describe handling stability for most vehicles. However, for vehicles with a locked differential or tandem rear axle, handling diagrams may be inadequate as the longitudinal forces on the two sides of the vehicle are not equal; see [22]. The new concept of the handling surface has been created to describe vehicle handling stability in these cases [23, 24].

To date, there has been too much focus on the handling stability of trucks and passenger cars, but few studies have attempted to characterize that of tractor semitrailers. Therefore, in this paper, the handling stability of tractor semitrailers is studied using handling diagrams, and the impact of vehicle design parameters and motion variables on the vehicle handling stability is analyzed. The research results have great importance for the development of active/passive safety control systems and for ensuring driving safety.

Given the importance of the number of nonsteering rear axles (on the tractor) on the handling stability of a tractor semitrailer and given that most tractors have one or two, tractor semitrailer when the tractor has two nonsteering rear axles and that when the tractor has one nonsteering rear axle are the two cases discussed in this paper. For simplicity, we refer to them as tractor semitrailers with two rear axles/one rear axle.

2. Handling Stability Analysis of the Tractor Semitrailer

First, we establish the handling equation to be used in plotting the handling diagram.

2.1. Review of Handling Equation for Simple Vehicles

In [14], Pacejka supposed that the steer angle is small, and the vehicle can be simplified to a bicycle model, and the handling equation for a simple vehicle can be expressed as

$$\delta - \frac{l}{R} = \alpha_f - \alpha_r = a_y\left(\frac{F_{zf}}{c_{\alpha f}} - \frac{F_{zr}}{c_{\alpha r}}\right), \tag{2.1}$$

where δ is the steering angle, l is the vehicle's wheelbase, and R is the turning radius. α_f and α_r are the side-slip angles of the front and rear tires, respectively. $c_{\alpha f}$ and $c_{\alpha r}$ are the cornering stiffness of the front and rear tires, respectively. F_{zf} and F_{zr} are the vertical loads of the front and rear tires, respectively. a_y is lateral acceleration.

The compliance factor K and the lateral acceleration are defined as follows:

$$K = \frac{F_{zf}}{c_{\alpha f}} - \frac{F_{zr}}{c_{\alpha r}}, \tag{2.2}$$

$$a_y = \frac{V^2}{gR}, \tag{2.3}$$

where V is driving speed.

2.2. Handling Equations for Tractor Semitrailers

Based on the handling equation for simple vehicles, Winkler [19] produced different handling equations for complex vehicles, which may be presented in any of the following forms:

$$\delta - \frac{l}{R} = \alpha_f - \alpha_r = f_1(a_y, V), \tag{2.4}$$

$$\delta - \frac{l}{R} = \alpha_f - \alpha_r = f_2\left(a_y, \frac{1}{R}\right), \tag{2.5}$$

$$\delta - \frac{l}{R} = \alpha_f - \alpha_r = f_3\left(V, \frac{1}{R}\right). \tag{2.6}$$

Different from (2.1), except for being a function of lateral acceleration, the tire-side slip angle of complex vehicles may be related to the turning radius (when considering multiple nonsteering rear axles) or the driving speed (when considering the hysteresis effect of the tires). Equation (2.6), which is just a complement to (2.4), and (2.5), cannot be used individually.

It can be seen from (2.1), (2.4), and (2.5) that the vehicle handling stability is determined by the difference between the side-slip angles of the front and rear tires. Unlike a single-unit vehicle, a tractor semitrailer is composed of two vehicle units—a tractor and a trailer. The latter is attached to the former at an articulated point, using a fifth wheel coupling. Therefore, handling stability analysis of a tractor semitrailer is more complex as it must take the handling stabilities of each vehicle unit into account. For simplicity, we suppose that the tire-ground adhesion coefficient is big enough, and the trailer will not experience side-slip. Then, the tractor semitrailer's handling stability will be determined by the difference between the side-slip angles of the tractor's front and rear tires.

According to market surveys, most tractors have one or two nonsteering rear axles, those with two being most popular. Considering the impact of multiple nonsteering axles on vehicle handling stability, the following handling equation introduced by Winkler [19] can be used as the handling equation for a tractor semitrailer with two rear axles:

$$\delta - \frac{l}{R} = \frac{(1/lR)\left(1 + c_{\alpha r}/c_{\alpha f}\right) \sum_{i=1}^{n} \Delta i^2}{n + a_y\left(F_{zf}/c_{\alpha f} - F_{zr}/c_{\alpha r}\right)}, \tag{2.7}$$

where Δi is the longitudinal distance from the compound rear axle of the tractor to the ith rear axle and the compound rear axle is located at the longitudinal position about which the vertical loads carried by all rear tires produce a net pitch moment of zero.

To simplify our analysis of the handling stability, we define the following quantity:

$$T = \frac{1}{2}\sum_{i=1}^{2}\Delta i^2. \tag{2.8}$$

The nonlinear characteristics of tires on heavy vehicles mainly reflect the relationship between the tires' vertical loads and cornering stiffness, which is commonly described by the following equation introduced by Frendo et al. [24]:

$$c_\alpha = c + c_1 F_z + c_2 F_z^2, \tag{2.9}$$

where c, c_1, c_2 are constants.

Heavy vehicle tires have more stiffness, which makes the tire side-slip angle smaller and keeps the relation between the cornering force and the cornering stiffness fairly linear. This fact can be expressed by

$$F_y = \alpha c_\alpha, \tag{2.10}$$

where F_y is the tires' cornering force.

Now we define the following quantities:

$$\begin{aligned} C(a_y) &= \frac{c_{\alpha r}}{c_{\alpha f}}, \\ K(a_y) &= \frac{F_{zf}}{c_{\alpha f}} - \frac{F_{zr}}{c_{\alpha r}}. \end{aligned} \tag{2.11}$$

According to (2.7)–(2.11), the handling equation for a tractor semitrailer with two rear axles can be written as follows:

$$\delta - \frac{l}{R} = \frac{T}{lR}(1 + C(a_y)) + a_y K(a_y). \tag{2.12}$$

The total differentials of $\delta - l/R$ and a_y can be solved to analyze the change in vehicle handling stability with respect to lateral acceleration:

$$d\left(\delta - \frac{l}{R}\right) = \frac{\partial\delta}{\partial V}\, dV + \left(\frac{\partial\delta}{\partial(l/R)} - 1\right) d\left(\frac{l}{R}\right), \tag{2.13}$$

$$da_y = \frac{2V}{gR}\, dV + \frac{V^2}{g}\, d\left(\frac{l}{R}\right). \tag{2.14}$$

According to (2.12), the partial differentials of δ with respect to V and l/R are as follows:

$$\frac{\partial\delta}{\partial V} = \frac{2V}{gR}\left[K(a_y) + a_y \frac{dK(a_y)}{da_y} + \frac{dC(a_y)}{da_y}\right], \tag{2.15}$$

$$\frac{\partial\delta}{\partial(l/R)} - 1 = \frac{T}{l^2}(1 + C(a_y)) + \frac{V^2}{gl}\left[K(a_y) + a_y \frac{dK(a_y)}{da_y} + \frac{dC(a_y)}{da_y}\right]. \tag{2.16}$$

Supposing that the turning radius remains constant, we can substitute (2.15) and (2.14) into (2.13) to give

$$\left.\frac{d(\delta - l/R)}{da_y}\right|_{R=R_c} = K(a_y) + \frac{dC(a_y)}{da_y} + a_y\frac{dK(a_y)}{da_y}. \tag{2.17}$$

Now, supposing that the driving speed remains constant, we can substitute (2.16) and (2.14) into (2.13) to give

$$\left.\frac{d(\delta - l/R)}{da_y}\right|_{V=V_c} = \frac{Tg}{lV^2}(1 + C(ay)) + \left[K(a_y) + a_y\frac{dK(a_y)}{da_y} + \frac{dC(a_y)}{da_y}\right]. \tag{2.18}$$

Equations (2.17) and (2.18) give the changes in vehicle handling stability with respect to lateral acceleration holding the turning radius and driving speed constant, respectively.

The handling diagram that is obtained by holding the turning radius constant is called the R-handling diagram, and the corresponding handling curves are called R-handling curves. Similarly the V-handling diagram and V-handling curves refer to the case where the driving speed is held constant.

For a tractor semitrailer with one rear axle, the handling equation and partial differential with respect to a_y are as follows:

$$\begin{gathered}\delta - \frac{l}{R} = a_y K(a_y), \\ \left.\frac{d(\delta - l/R)}{da_y}\right|_{V=V_c} = \left.\frac{d(\delta - l/R)}{da_y}\right|_{R=R_c} = K(a_y) + a_y\frac{dK(a_y)}{da_y}.\end{gathered} \tag{2.19}$$

3. Solution of the Tractor Tires' Vertical Load

From Section 2.2, we know that the handling stability of a tractor semitrailer is actually determined by the vertical load distribution over the tractor's front and rear tires.

For analytical clearness, the tractor and its trailer are separated at the articulated point, and corresponding forces are applied to both vehicle units, as shown in Figure 1.

Under steady-state turning, the articulated angle θ between the tractor and trailer always remains small. Thus, we can say

$$\cos\theta \approx 1, \qquad \sin\theta \approx 0. \tag{3.1}$$

The semitrailer is partly supported by the tractor once the two are connected. The load that comes from the trailer and is carried by the tractor can be expressed by

$$F = \frac{b'}{l'}(m_{s2} + m_c)g, \tag{3.2}$$

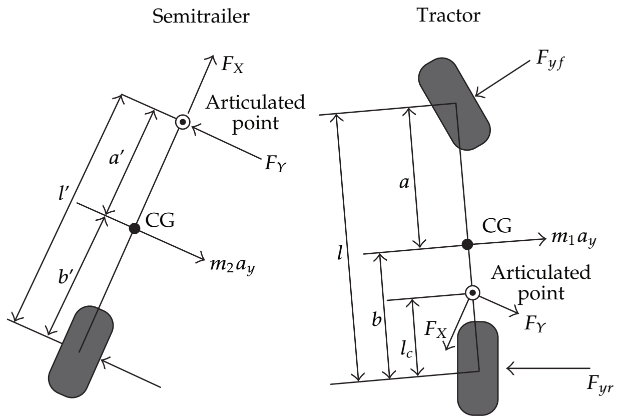

Figure 1: Representation of tractor semitrailer: main dimensions and lateral forces.

where b' is the distance from the center of the trailer's sprung mass to the compound rear axle, l' is the distance from the center of the kingpin to the compound rear axle, m_{s2} is the trailer's sprung mass, and m_c is the loaded mass.

The fifth wheel is installed on the rear of the tractor, which moves the center of gravity (CG) of the tractor's sprung mass backwards when it is towing a trailer. The distance the CG moves can be expressed by

$$\Delta l = \frac{(b - l_c)b'(m_{s2} + m_c)}{l'(m_{sf1} + m_{sr1}) + b'(m_{s2} + m_c)}, \tag{3.3}$$

where b is the distance from the CG of the tractor's sprung mass to its compound rear axle, l_c is the fifth wheel lead, which is the distance from the center of the fifth wheel's jaw to the CG of the tractor's sprung mass, and m_{sf1} and m_{sr1} are the sprung masses of the tractor's front and rear axles, respectively.

According to (3.2) and (3.3), the vertical loads of the tractor's front and rear axles when the tractor is towing a trailer can be presented as follows:

$$\begin{aligned} F_{zf} &= \left[(m_{sf1} + m_{uf1}) + \frac{l_c}{l}\frac{b'}{l'}(m_{s2} + m_c)\right]g, \\ F_{zr} &= \frac{a}{l}(m_{sr1} + m_{ur1})g + \frac{l - l_c}{l}\frac{b'}{l'}(m_{s2} + m_c)g, \end{aligned} \tag{3.4}$$

where m_{uf1} and m_{ur1} are the unsprung masses of the tractor's front and rear axles, respectively, and a is the distance from the CG of the tractor's sprung mass to the front axle.

Side-to-side lateral load transfer is generated when a lateral force acts on the vehicles. As seen from Figure 2, the lateral load transfers of the tractor's front and rear tires can be expressed by

$$\begin{aligned} \Delta F_{zf} &= \frac{a_y m_s g}{d_f}\left[\frac{h_s}{1 + k_r/k_f - m_s g h_s/k_f} + \frac{b - \Delta l}{l}h_f\right], \\ \Delta F_{zr} &= \frac{a_y m_s g}{d_r}\left[\frac{h_s}{1 + k_f/k_r - m_s g h_s/k_r} + \frac{a + \Delta l}{l}h_r\right], \end{aligned} \tag{3.5}$$

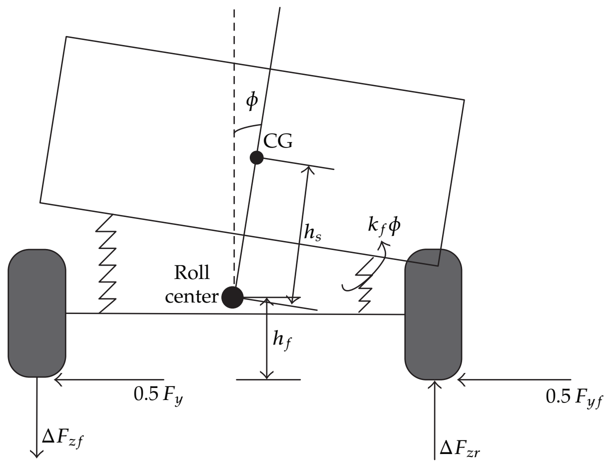

Figure 2: Roll plane model of tractor.

where m_s is the tractor's sprung mass, and the load coming from the trailer is included. d_f and d_r are the tractor's front and rear treads, respectively. h_f and h_r are the distances from the ground to the tractor's front and rear roll centers, respectively. h_s is the distance from the CG of the tractor's sprung mass to the tractor's roll axis.

From (3.4)-(3.5), we can obtain the vertical loads of the tires on both sides of the front and rear axles.

4. Simulation and Discussion

First, we introduce the characteristics of the handling diagram before looking at the handling stability simulation for a tractor semitrailer.

4.1. Introduction to Handling Diagrams

A handling diagram for a passenger car under different driving conditions, obtained using (2.1)–(2.3), is presented in Figure 3. In a handling diagram, an upward slope to the left indicates understeer, a vertical slope indicates neutral steer, and an upward slope to the right indicates oversteer. The smaller is the slope, the more likely the vehicle is to understeer or oversteer (see in [15]). In Figure 3, the distance between points A and B is the steering angle needed under the specified driving conditions.

Based on the characteristics of the handling diagram shown, equivalent definitions for understeer, neutral steer, and oversteer for complex vehicles are given in Table 1 (see in [19]).

4.2. Vehicle Description

The vehicle characteristics that were used in our numerical simulation of the handling stability of a tractor semitrailer with two rear axles are listed in Table 2 (see in [25]). The tractor is a three-axle vehicle unit with single tires on the front axle and dual tires on the two rear axles. The trailer's rated load is 30,000 kg.

For the tractor semitrailer with one rear axle, the characteristics are the same as for the two rear axle case, except for the tractor's wheelbase, which is 3.5 m, and the number of tractor tires, which is 8.

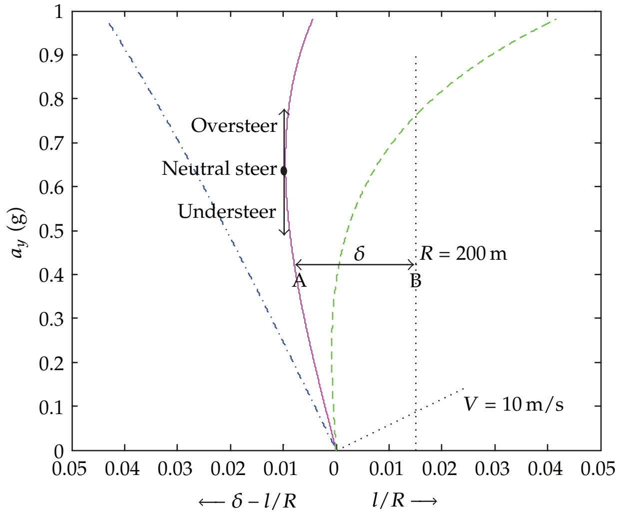

Figure 3: Handling diagram for a passenger car.

Table 1: Equivalent definitions for understeer, neutral steer, and oversteer of a complex vehicle.

At a constant radius	Oversteer	$d(\delta - l/R)/da_y\vert_{R=R_c} < 0$	$\partial\delta/\partial V < 0$
	Neutral steer	$d(\delta - l/R)/da_y\vert_{R=R_c} = 0$	$\partial\delta/\partial V = 0$
	Understeer	$d(\delta - l/R)/da_y\vert_{R=R_c} > 0$	$\partial\delta/\partial V > 0$
At a constant velocity	Oversteer	$d(\delta - l/R)/da_y\vert_{V=V_c} < 0$	$\partial\delta/\partial(l/R) < 0$
	Neutral steer	$d(\delta - l/R)/da_y\vert_{V=V_c} = 0$	$\partial\delta/\partial(l/R) = 0$
	Understeer	$d(\delta - l/R)/da_y\vert_{V=V_c} > 0$	$\partial\delta/\partial(l/R) > 0$

The load distribution across the tractor's front and rear axles when it is towing a trailer is determined by the fifth wheel lead, which can be adjusted within a certain range to allow the fifth wheel to engage with the kingpin. The fifth wheel for the tractor with two rear axles is arranged between the two rear axles, and the fifth wheel lead is about 0.3 m. According to collected statistics, the distance between the two rear axles is generally 1.45 m, 1.4 m, 1.37 m, 1.35 m, 1.3 m, and so forth, and 1.35 m is the most common distance. Therefore, the adjustment range for the fifth wheel lead for a tractor with two rear axles is somewhere between 0 and 0.675 m.

To analyze the influence of the fifth wheel lead on the handling stability of a tractor semitrailer with one rear axle, we assume that the adjustment range is the same as for the tractor with two rear axles.

All rear tires are assumed to be the same and to support equal loads. Taking lateral load transfer into consideration, tire cornering stiffness can be calculated as the average of the right and left tires' cornering stiffness, and the vertical load can also be assumed to be the average of the right and left loads.

The constants in (2.9) are assumed to take the following values (see in [25]):

$$\begin{aligned} c &= 5000\,\mathrm{N/rad}, \\ c_1 &= 10.1/\mathrm{rad}, \\ c_2 &= -11.1/(\mathrm{N}\cdot\mathrm{rad}). \end{aligned} \tag{4.1}$$

Table 2: Characteristics of the tractor semi-trailer with two rear axles.

Parameter	Value	Parameter	Value
m_{sf1}	5069 kg	m_{sr1}	2431 kg
m_{uf1}	790 kg	m_{ur1}	1590 kg
a	1.288 m	b	2.687 m
k_f	140000 N/rad	l_c	0.3 m
k_r	202000 N/rad	d_f	2.2 m
d_r	1.8 m	h_f	0.5 m
h_r	0.5 m	h_s	0.242 m
m_{s2}	6000 kg	a'	4.77 m
b'	3.34 m	l	3.975 m
l'	8.11 m	T	0.36 m

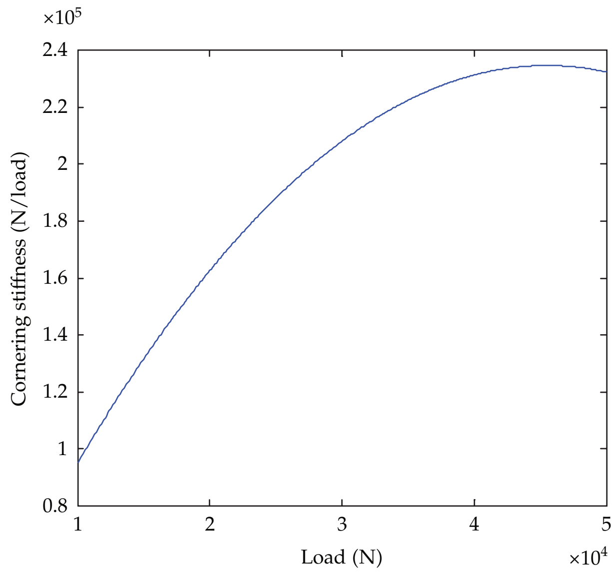

Figure 4: Tire cornering stiffness as a function of vertical load.

Based on the vehicle characteristics presented in Table 2 and the tire property parameters, we can calculate curves showing tire cornering stiffness and the ratio of rear tires' to front tires' cornering stiffness. These are presented in Figures 4 and 5.

4.3. Influence of Vehicle Parameters on Handling Stability

We use Matlab to simulate the influence of different vehicle parameters on the handling stability of the tractor semitrailer with one or two rear axles.

4.3.1. Tractor Semitrailer with Two Rear Axles

We use (2.12) to simulate the vehicle handling stability of a tractor semitrailer with two rear axles under either a constant driving speed or turning radius. The simulation results are presented in Figures 6 and 7.

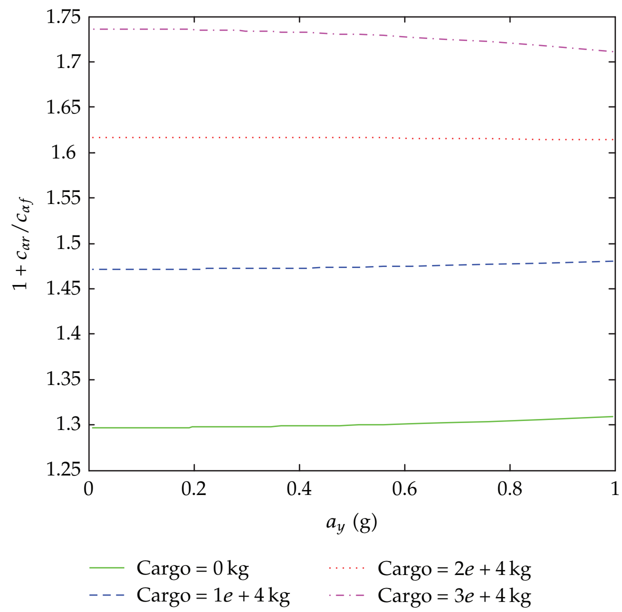

Figure 5: Ratio of rear tire's to front tire's cornering stiffness.

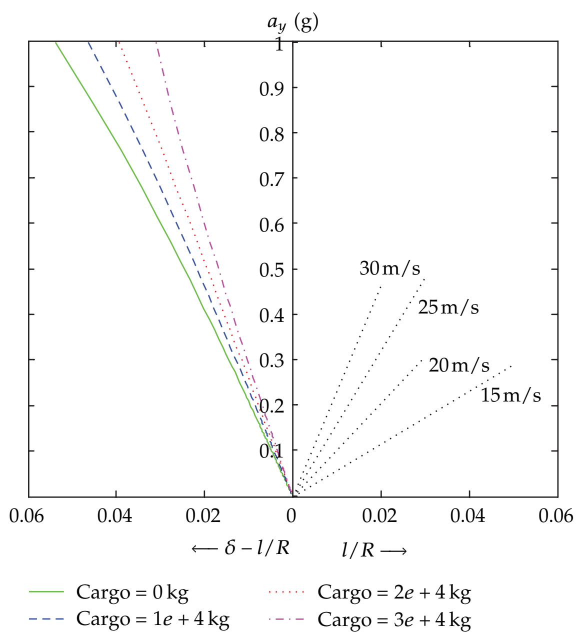

Figure 6: V-handling diagram for tractor semitrailer with two rear axles.

As can be seen in Figures 6 and 7, the V-handling curves and R-handling curves for a tractor semitrailer with two rear axles are quite similar to one another as the other parameters vary. Figure 5 shows that the range of $1 + c_{\alpha r}/c_{\alpha f}$ is 1.3–1.75. As T/lR is quite small for most tractors, $T/lR(1 + C(a_y))$, the multiple nonsteering rear axles term in (2.12) has quite a small impact on the vehicle handling stability. However, a slight influence can still be seen in the

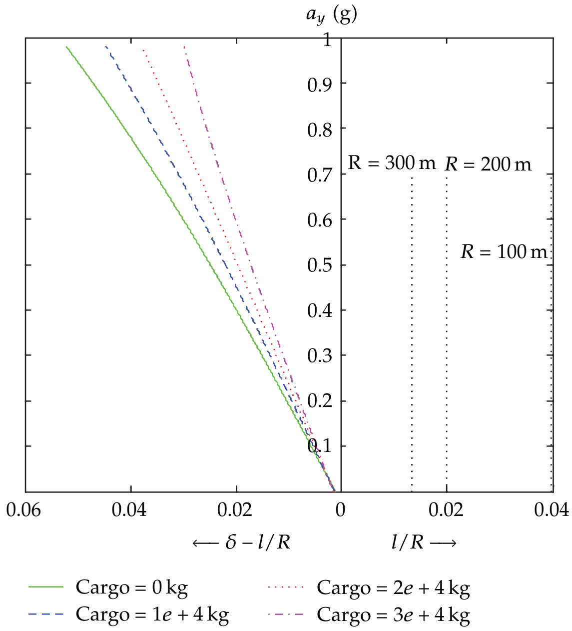

Figure 7: *R*-handling diagram for tractor semitrailer with two rear axles.

R-handling diagram, as the starting points of the *R*-handling curves are not at the origin but at a positive value in the direction of the $\delta - l/R$ axis. The same explanation can also be obtained from (2.17) and (2.18).

The most important finding that can be drawn from Figures 6 and 7 is that a tractor semitrailer with two rear axles has great handling stability within the trailer's rated load range. The tractor has four times as many rear tires as front tires, making both the vertical load and the load transfer of a single rear tire smaller than those of a single front tire. In addition to the rear tire's strong stiffness, $K(a_y)$ in (2.12) is positive, and the vehicle has great handling stability. However, there is a fall in the value of $dC(a_y)/da_y$ in (2.17) due to the increase in loaded mass, and this becomes negative when the loaded mass reaches a certain value. As the minimum value $dC(a_y)/da_y$ can reach is −0.06, which in absolute value terms is larger than $K(a_y)$ (0.028–0.0525), the vehicle handling stability becomes poor under an increase in the loaded mass.

Therefore, the excellent handling stability of a tractor semitrailer with two rear axles owes more to its rear tires than to its multiple nonsteering rear axles. Unlike the conclusions drawn in [19], we find that multiple nonsteering rear axles do not strengthen the vehicle's handling stability but weaken it.

A handling diagram for a tractor semitrailer with two rear axles and varying fifth wheel leads is presented in Figure 8. The influence of the fifth wheel lead on vehicle handling stability is quite small. However, the larger the fifth wheel lead is, the better handling stability the vehicle has.

4.3.2. Tractor Semitrailer with One Rear Axle

For a tractor semitrailer with one rear axle, the *V*-handling and *R*-handling curves coincide. However, for analytical convenience, we present the two diagrams separately, in Figures 9 and 10.

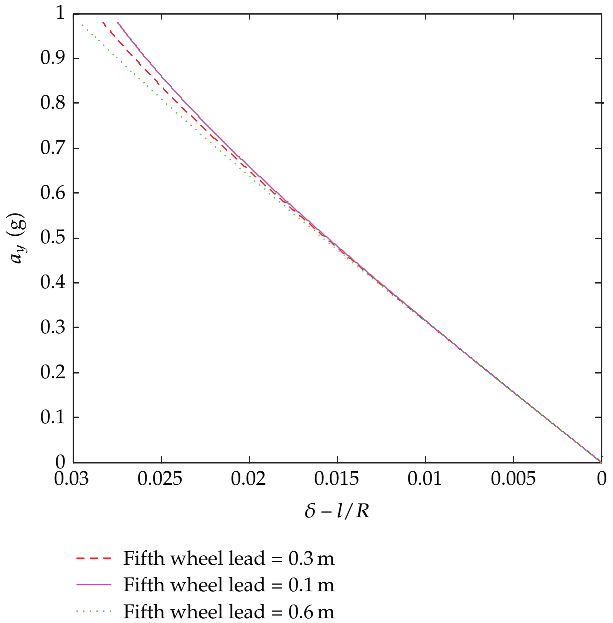

Figure 8: Handling diagram for a tractor semitrailer with two rear axles and varying fifth wheel leads.

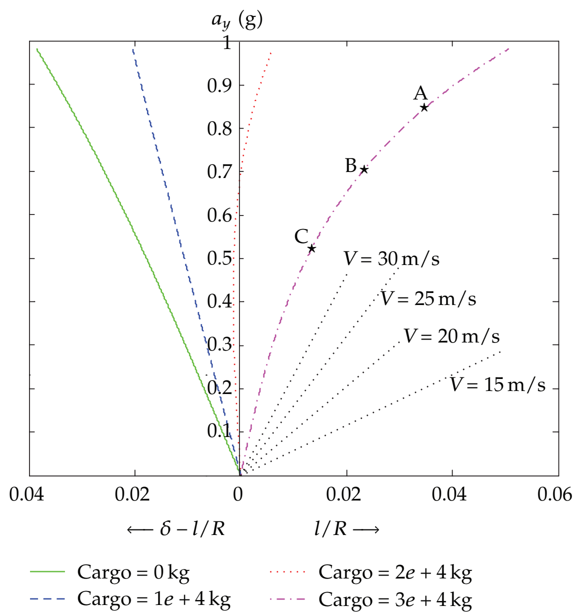

Figure 9: V-handling diagram for tractor semitrailer with one rear axle.

As Figures 9 and 10 show, vehicle handling stability quickly becomes poor as the loaded mass increases. In a fully loaded situation, the vehicle handling stability presents an understeering characteristic in a narrow lateral acceleration range and then turns into a neutral steer or oversteering situation.

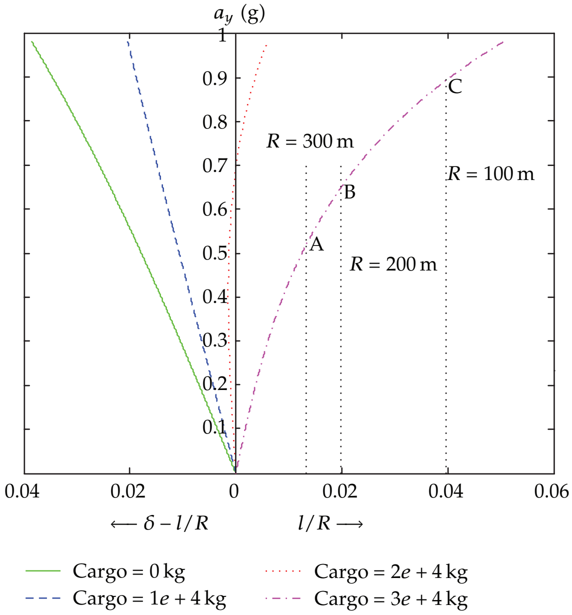

Figure 10: R-handling diagram for tractor semitrailer with one rear axle.

Figure 9 shows that the driving speed has a large impact on the vehicle handling stability when the loaded mass is large. When the loaded mass is 30,000 kg and driving speeds are 20 m/s, 25 m/s and 30 m/s, respectively, the critical lateral acceleration values at which instability may occur are at points A (0.8446 g), B (0.7031 g), and C (0.5203 g). An increase in driving speed will further weaken the vehicle handling stability and eventually result in instability. Considering heavy vehicles' rollover thresholds, such vehicles are prone to rollover accidents at low speeds and handling instability accidents at high speeds, even if the turning radius is quite large (R = 177 m at point C).

Figure 10 shows that, when the loaded mass is 30,000 kg and the turning radii are 100 m, 200 m, and 300 m, respectively, the intersection points between the l/R lines and the R-handling curve occur at points C, B, and A. The physical meaning of these intersection points is that the vehicle loses steering capacity ($\delta = 0$) and rotates on its axis. The corresponding driving speeds for points A, B, and C are 39 m/s, 35.67 m/s, and 29.6 m/s, respectively, which are obtained from (2.3). Taking into account the strong impact of driving speed on vehicle handling stability, even if the turning radius is large and there is no apparent road curvature, the vehicle will still lose its original stability in these conditions.

Based on the previous analysis, a vehicle handling stability threshold defined by driving speed is more appropriate than one defined by lateral acceleration. This implies that it is important to set limits on the driving speeds of heavy vehicles on highways.

The handling diagram for a tractor semitrailer with one rear axle and varying fifth wheel leads is presented in Figure 11. The same conclusions can be drawn as in the case of two rear axles. Due to the poor handling stability of the tractor with one rear axle, the fifth wheel lead should be as large as possible when the loaded mass is large.

4.4. Conclusions

In this paper, we analyze the handling stability of tractor semitrailers with one or two rear axles, based on handling diagrams. The following conclusions are obtained.

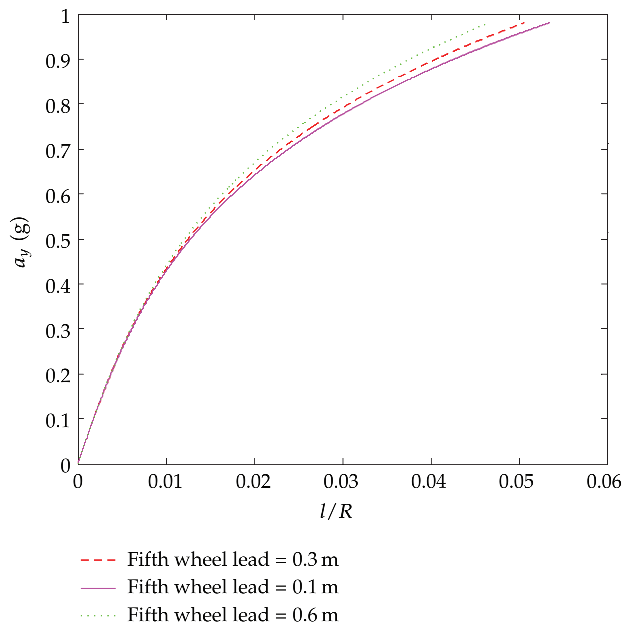

Figure 11: Handling diagram for a tractor semitrailer with one rear axle and varying fifth wheel leads.

(1) Tractor semitrailers with two rear axles have better handling stability than those with just one. Within the rated load range, the former always show good steering performance. This result is due to the larger number of rear tires on the two-rear-axle vehicle.

(2) For a tractor with one rear axle, towing a trailer with a suitable total mass and driving at a low speed are quite important. This tractor semitrailer will lose handling stability when overloaded or if driven at high speeds. The vehicle may even lose steering capacity at high speeds.

(3) Driving speed has much more influence on vehicle handling stability than the turning radius. Even on a gentle curve, these vehicles should not be driven at speeds above a certain level.

(4) Fifth wheel lead has a slight influence on the handling stability of tractor semitrailers with one and with two rear axles. However, for tractors with one rear axle, it is especially important that the fifth wheel lead should be as large as possible in order to improve vehicle handling stability.

Since we make the assumption in deriving the handling equations that the tire-ground adhesion coefficient is sufficiently large, the handling equations are limited to analyzing handling stability for vehicles driven under certain road and driving conditions only. Thus, handling stability analysis for tractor semitrailers driven on slippery roads will be conducted in a future study.

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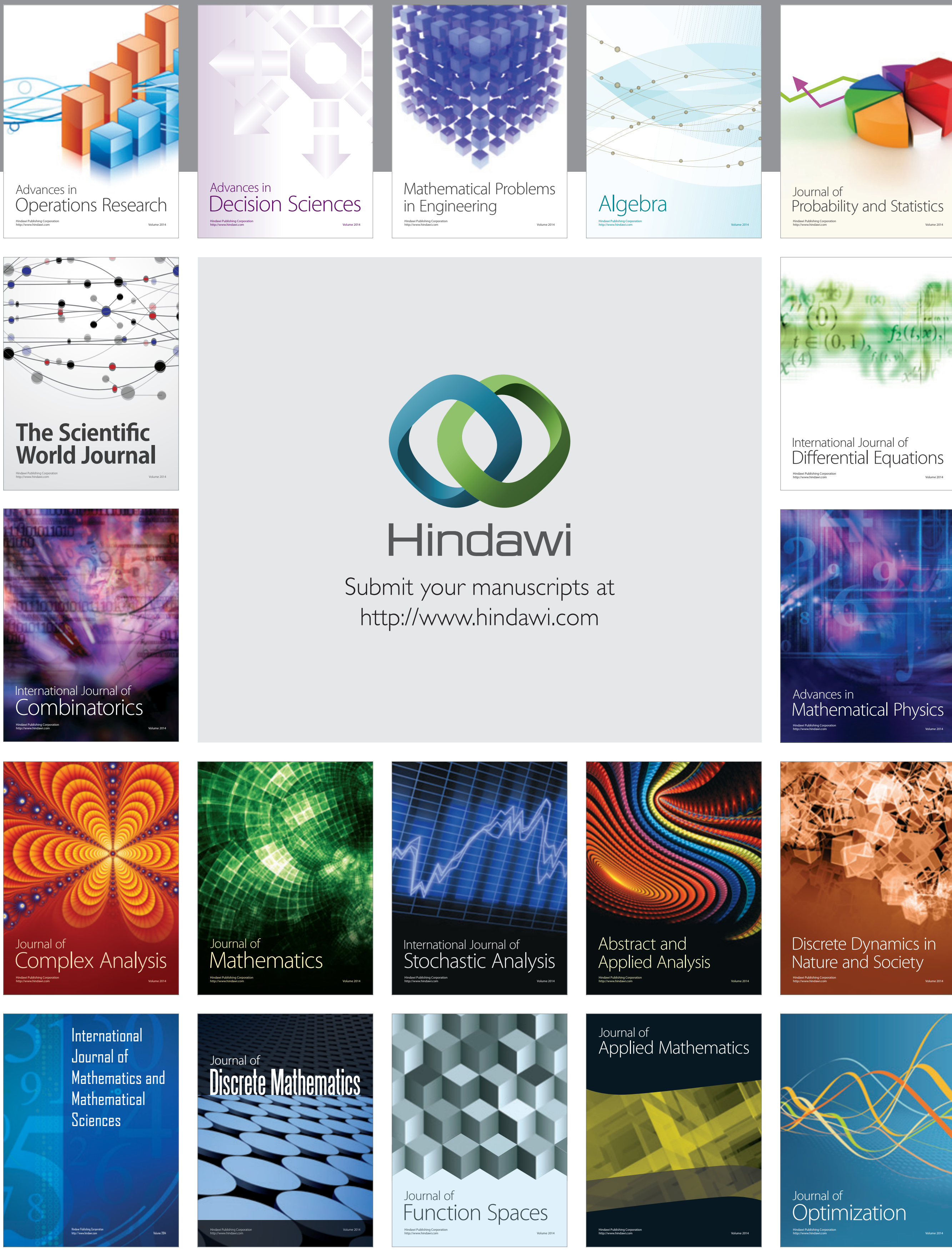
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