The Old Man and His Caravan

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KEY FINDINGS

The rear end of caravans is sensitive to additional loading potentially causing a reduction of the critical speed above which fishtailing might manifest.

ABSTRACT

A sample caravan is presented to illustrate the effect on critical speed by adding LPG bottles. spare tyres and additional water. By using well-established formulae, the sensitivity of bad loading is demonstrated. Lateral tyre stiffness is identified as a most important contributor to caravan fishtailing.

KEYWORDS

Tractrix, sideslip, loading, fishtailing, snaking, caravan, tyre.

INTRODUCTION

The appeal of caravanning is on the increase. The onset of an aging population ensures there is no shortage of grey nomads cruising the highways and byways of Australia. One travel magazine reports a doubling over the last 3 years for the grey nomads alone.

In the culture of Four-Wheel Drive (4WD) owners, there exists bragging rights adorning the man cave walls or across the bar to the tired ear of the ever-patient barman. Even status levels in the 4WD community exist, having conquered the most challenging Australian Outback road or track.

Our ‘Old Man’ in Figure 1, inspired by the rugged courage of Ernest Hemingway’s “Old man and the Sea” aspires to notch up a journey of great achievement. Capturing his imagination for a very long time has been the Oodnadatta Track stretching gravel for over 600 km and promising sights like the on-again, off-again Lake Eyre that disappears as mysteriously as it reappears. A worthy challenge for man and machine.

Figure 1 – The Old Man and his caravan.

The warnings displayed on the Oodnadatta Track in Figure 2 are not entirely surprising to our Old Man and he ponders the wisdom of adding the extra weight to his caravan.

Figure 2 – Warning signs on the Oodnadatta Track.

Adding mass to a caravan should proceed with caution according to popular advice. (Rivers, 2013). Surely a couple of spare wheels won't make that much difference? The caravan community is generally aware of the need to have an adequate hitch load. However, the idea that as long as you balance the weights front to back, is pervasive and may mislead.

There are many individual dashcam videos published on the Internet that illustrate bad loading consequences. One such video is a compilation of fishtailing events of badly loaded trailers and is posted on YouTube by Thematic Compilations. The video may be viewed here:

https://www.youtube.com/watch?v=Z7Kfl97b57s&feature=youtu.be&t=9

Stills of the first video were taken and posted to Figure 3, showing travel sequence from left frame to right frame, while overtaking to a teetering point. The truck speed showed 69 mph (110 km/h). The caravan was going faster. The additional rear load (red arrow) is significant and is a long way from the axle group so producing a greater yaw moment.

Figure 3 – Video snapshots of fishtailing event of a badly loaded caravan.

Thus, the additional load may have contributed to the terminal event.

CAUSES OF CARAVAN INSTABILITY

Wind, road conditions and steering errors are on the first line of cause, all of which are beyond scope for this paper. There are however, 5 major contributors to fishtailing that are intrinsic to the caravan and tow vehicle, as follows:

1. Bad loading.
2. Highly flexible tyres.
3. High centre of gravity.
4. Axle steering.
5. Critical speed of caravan.
    a. Mass Moment of Inertia
    b. Cornering Stiffness Co-efficient
    c. Before-After

These 5 points are interrelated but are discussed under their own heading.

1. Bad Loading.

When the loaded caravan centre of gravity is on or behind the axle or axle group centreline then the load on the hitchpoint is upwards. This creates an uplift on the rear axle of the tow vehicle denying the tow vehicle full directional stability. This is shown exaggerated in Figure 4:

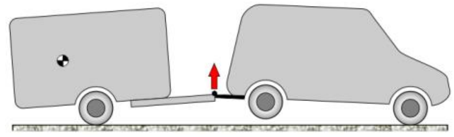

Figure 4 – Unloading tow vehicle rear axle weight.

Similarly, the tow vehicle directional control can be destabilized by having the caravan centre of gravity too far forward. This is shown exaggerated in Figure 5.

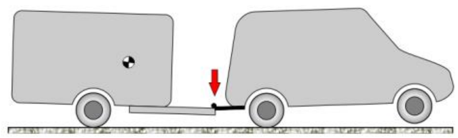

Figure 5 – Unloading tow vehicle front axle weight.

Hint for the Old Man: Invest in a tongue weight scales to eliminate guesswork.

2. Highly Flexible Tyres.

High lateral tyre flexibility contributes to the fishtailing phenomenon. The contact patch distorts and creates side slip. Side slip steers the caravan into an oscillating direction. Lateral stiffness is a desirable tyre property that gives caravans directional stability. This property comes about as a result of tread thickness and width. With reference to Section Y-Y of Figure 6 shear resistance is proportional to the cross-sectional area ***B x D*** and bending resistance is proportional to its section modulus ***B x D***^{2}, *ceteris paribus*[1]. Thus, in broad terms, it can be said that tyre width is a significant determinant of tyre stiffness.

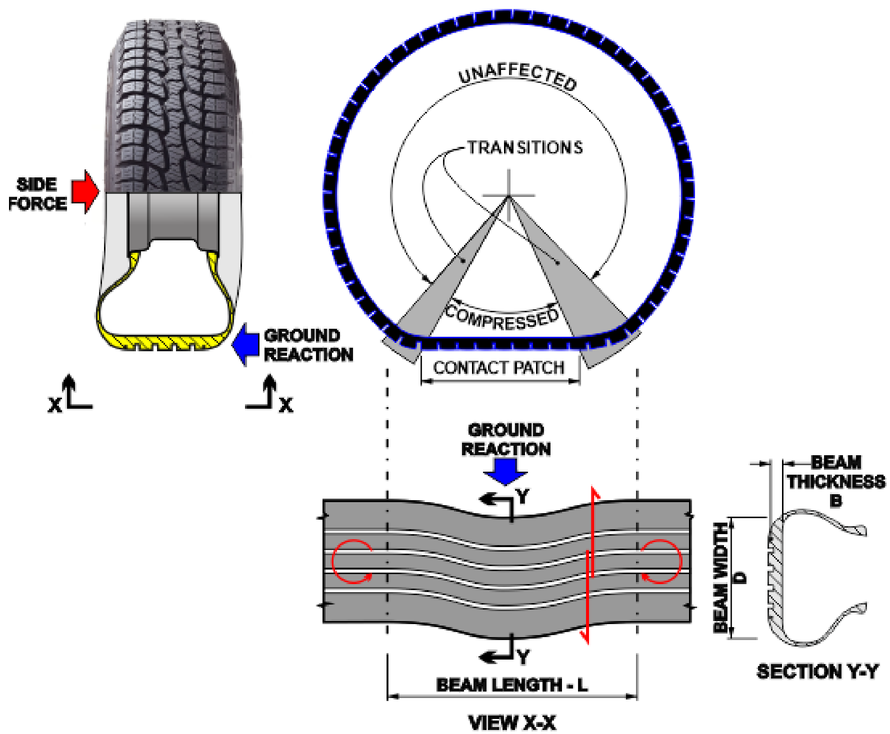

Figure 6 –Tread laid flat showing bending and shear action.

Hint for the Old Man: Buy the widest tyre that fits under the wheel arch, allowing for suspension travel.

[1] All other things equal

3. *High Centre of Gravity.*

Loading overhead cupboards with heavy objects will raise the centre of gravity of the caravan. This, in turn, will lower the body roll natural frequency. In the principle of superposition (Fatima, 2018), the action of body roll can increase the amplitude of yaw oscillation. As a result, the oscillating system receives more yaw momentum which may be potentially irrecoverable. The general idea is expanded in Brell & Thambiratnam (2020a).

Hint for the Old Man: All caravans should have torsion bar suspensions to stiffen body roll.

4. *Axle steering.*

A pot hole can cause a caravan axle to steer in a direction other than remain in drawbar alignment with tow vehicle centreline. Body roll, too, can create an articulation angle with the tow vehicle. Both can initiate an irrecoverable fishtailing event. The misalignment of centrelines caused by axle steering is illustrated in Figure 7.

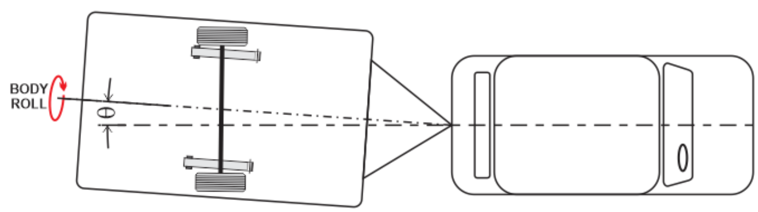

Figure 7 –Plan view of axle steering

Under conditions of body roll, there is a transfer of weight from one end of the axle to the other. This causes one wheel to move forward (lengthens in Figure 8) and the other wheel to move back (shortens in Figure 8). The result is that the axle temporarily misaligns (Θ) to the caravan centreline. This is illustrated in Figure 7. It is the journey to (Θ) and back from (Θ) that builds angular momentum and risks devastating consequences.

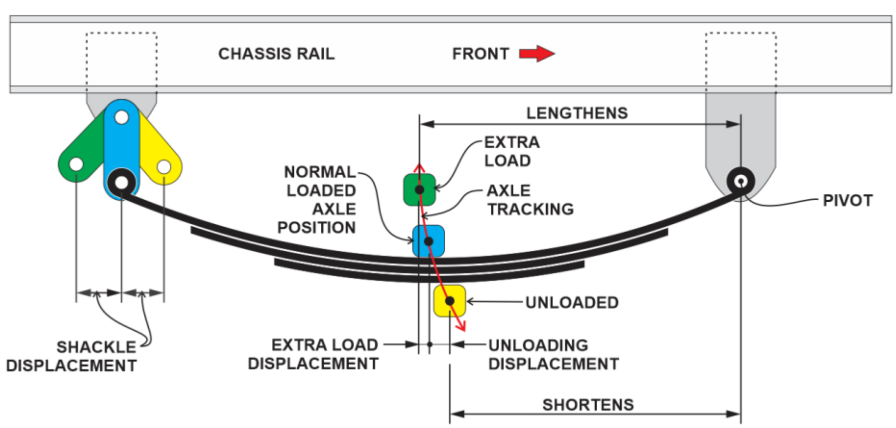

Figure 8 – Mechanism of axle steering

Hint for the Old Man: Reduce body roll by the fitment of torsion bar suspension.

5. *Critical speed of caravan.*

Many undergraduate texts require a study of the failure of the Tacoma Narrows Bridge, possibly the World's most spectacular failure. The cause was ascribed to aeroelastic flutter. The bridge lasted about 4 months before a wind at the right speed excited the bridge to resonance, then destruction. (Harish, 2020).

Mechanical systems need only a relatively small stimulus at the resonant frequency to provide large oscillations in the structure. The bow wave of an overtaken truck coupled with a fast lane change, a pot hole with or without avoidance manoeuvres or a gust of wind can direct a caravan and tow vehicle into a natural frequency dance to destruction.

Dashcam video footage on the Internet show the natural frequencies of these dances ranging from 0.5 to 1.0 Hz (Brell & Thambiratnam, 2020a).

Genta & Genta (2017) offer an equation for theoretical critical velocity *(V_{CR})* as follows, where ***(C)*** is the tyre cornering stiffness and (***L***) is the caravan wheelbase.

$$V_{CR} = \frac{1}{2} \cdot \sqrt{\frac{C \cdot L^3}{J_H}} \qquad \text{Equation 1}$$

Where $\boldsymbol{J_H}$ is the mass moment of inertia calculated at the hitchpoint.

Exceeding the critical speed does not mean automatic fishtailing to destruction. For that, the caravan needs the right stimulus, not unlike the wind in the aeroelastic flutter example above.

Having read about caravan critical speed in the popular press, our grey-bearded fictional friend in Figure 1 wanted to know if he could safely fit two 15 kg LPG bottles at the front and two spare tyres (35 kg) together with 105 litres of water at the back for his Oodnadatta Odyssey.

We assume the following, where the notes are numbered to follow the numbers in Figure 9:

1. Hitchpoint – simple moments in the vertical plane about the axle shows 70 kg downforce at hitchpoint for the caravan before the extra loading.
2. LPG Bottles – full weight including bracketry is estimated at 50 kg for the two.
3. Caravan Weight – before extra loading is M=630 kg.
4. Axle Centre is 4.0 m from hitchpoint.
5. Water and spare tyres including support structure estimated at 175 kg.

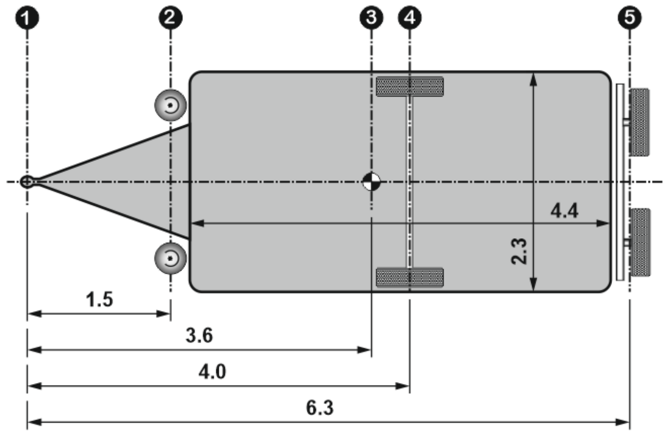

Figure 9 – Physical dimensions of the caravan.

The calculated centre of gravity in Figure 9 is before the appurtenances are added. The effect of weight distribution of LPG bottles, water and spare tyres is calculated in the annotated graphic of Figure 10.

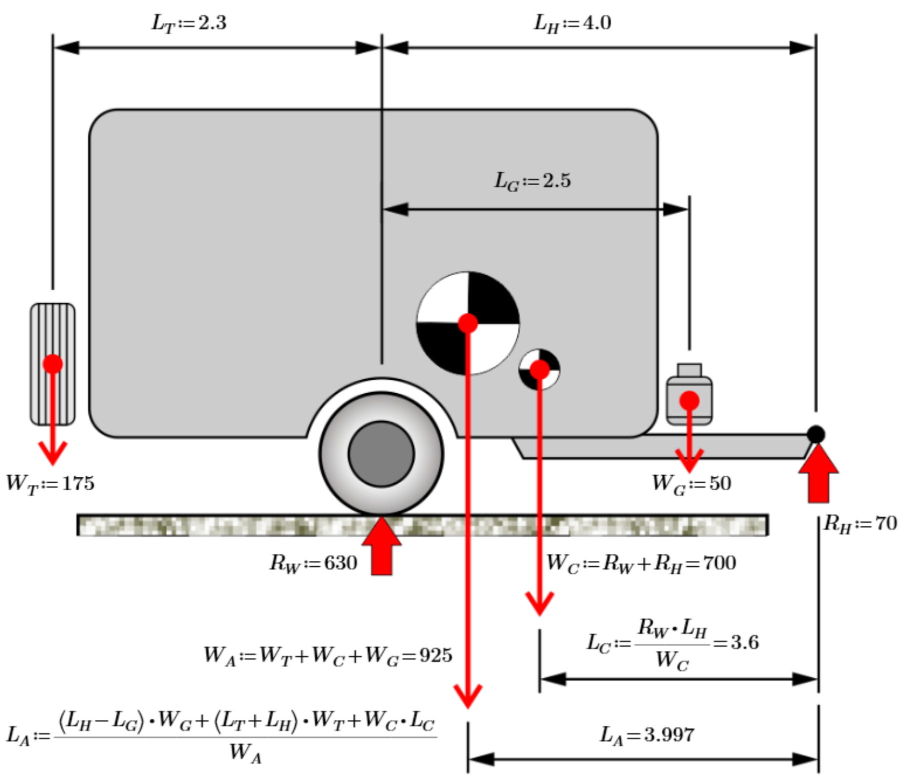

Figure 10 – Weight distribution after adding appurtenances

It will be noted from Figure 10, that the estimated total weight ***(W$_A$)*** is now 925 kg positioned approximately above the axle. The hitch load becomes zero.

5. Critical speed of caravan - Mass Moment of Inertia

There are two mass moments of inertia, the first about the caravan centre of gravity in the fishtailing plane. The centroidal moment of inertia is approximated as a flat plate (Jones, 2020), where ***(a , b)*** refer to length and width of the caravan and (W_C) being the centroidal weight.

$$J_C = \frac{W_C}{12} \cdot \left(a^2 + b^2\right) \qquad \text{Equation 2}$$

The second part of calculated mass moment of inertia makes use of the parallel axis theorem (OpenStax, 2020). Equation 3 refers, where ***(W)*** is the mass under consideration and ***(d)*** is the distance from the hitchpoint.

$$J_P = \sum \left(W_i \cdot d_i^2\right) \qquad \text{Equation 3}$$

Equation 2 & 3 are evaluated and posted to Table 1.

Table 1 - Mass moment of inertia of the Old Man's caravan

INERTIA MOMENT	*EQUATION*	*BEFORE*	*AFTER*
Centroidal	$\frac{W_C}{12} \cdot \left(a^2 + b^2\right)$	***1,438***	***1,438***
Parallel Axis	$W_C \cdot d_C^2$	***9,072***	***9,072***
LPG etc	$W_G \cdot d_G^2$	**-**	***113***
Tyre etc	$W_T \cdot d_T^2$	**-**	***6,946***
Totals (J_H)		***10,510 kgm***^{2}	***17,569 kgm2***

5. Critical speed of caravan - Cornering Stiffness Co-efficient

A good defence against trailer fishtailing is ensuring tyres are fitted that are laterally stiff. Brell & Thambiratnam, (2020) compared two tyres of identical outside diameter but different aspect ratio and showed yaw energy input into the fishtailing phenomenon to vary up to 400%. At the heart of the improvement was the cornering stiffness.

Getting cornering behaviour of tyres is not a simple matter of going to one's tyre retailer and asking the question. Tyre manufacturers don't appear to offer this quintessential attribute. In their defence, there are many variables such as load, pressure, road condition, temperature and speed to name a few. Some authors have published test results on the Internet. eg (Agalgaonkar, 2019), (Beato, 2000).

We choose test data published by Miyashita & Kabe (2005) for a 195/65R15 tyre as the tyre for Figure 1.

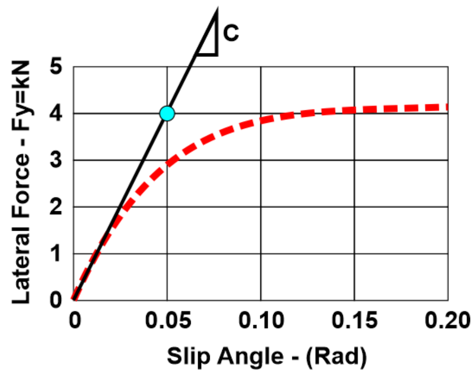

Figure 11 – Lateral tyre performance of Old Man's caravan

The cornering co-efficient can be derived from Figure 11 being the slope of the linear portion of the Lateral Force – Slip Angle graph. A convenient point is at the blue dot where the lateral force is 4000N and the corresponding slip angle is 0.05 radians. Thus, the cornering co-efficient is 80,000 N/rad (4000/0.05). There being two wheels, the axle co-efficient is C=160,000 N/rad to be used in the ensuing equations.

5. Critical speed of Old Man's caravan - Before-After

All that remains here is a calculation for critical speed of the Old Man's caravan before fitment of the appurtenances and notionally after. The effect may have implications for his proposed Oodnadatta Odyssey. The effect on his caravan's critical speed is posted to Table 2.

Table 2 – Critical speed of Old Man's caravan

ITEM	REFERENCE	BEFORE	AFTER
Mass Moment of Inertia *(J_H)*	***Table 1***	***10,510 kgm²***	***17,569 kgm2***
Cornering Co-efficient *(C)*	***Figure 11***	***160,000 N/Rad***	***160,000 N/Rad***
Critical Speed *(V_{CR})*	***Equation 1***	***56 km/h***	***43 km/h***

As a result of adding the LPG bottles, spare tyres and water, the calculated critical speed would reduce from 56 km/h to 43 km/h.

Bad News for the Old Man

The study raised some concerns for the Old Man and his proposed Oodnadatta Odyssey. The calculation results from Equation 1 assume that the hitchpoint travels in a straight line. The equation is derived from vibration theory and reflects the natural frequency of the swaying system. The potential uplift shown in Figure 10 ***($R_H = 0$)*** may affect this assumption. Thus, the critical velocity in Table 2 may not even be achievable.

The maximum Aggregate Trailer Mass (ATM) allowed for his caravan is 750 kg. Not having trailer brakes would cause the caravan to be in breach of the road rules at 925 kg ATM.

Whilst there may not be hard and fast rules with regard to tow ball weights, ***($R_H = 0$)*** would contravene general guidelines of 5 to 10% of ATM.

Then there are practical considerations, like the age of the caravan. Likely in that vintage the structure was made from timber. If termites haven't taken hold then there is dry rot to be considered. Then there are the ubiquitous corrugations…

Figure 12 – Endless corrugations of the Oodnadatta Track

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