CARAVAN DYNAMICS

by Collyn Rivers

Effects and their causes are often misunderstood. In some parts of the world, thunderstorms are, to this day, perceived as the anger of various gods. Plants may grow quicker if talked to - because talking exudes carbon dioxide - and that's what plants thrive on!

Over 60 years or more it has been virtually an article of faith that a caravan's tow ball loading should be a percentage of trailer weight. In Australia, that is 10%; in Europe 7%. I believed this too - until 2005.

Early experience showed that caravans, like arrows, must be front-heavy to travel straight. Back then, most caravans were 3.5-5.0 metres long, weighed about 1000 kg, and had centre kitchens. Around 70 kg tow ball weight was about right. The few that were longer needed a bit more (100 kg or so) but most mega-vans back then had axles at the front and rear. As longer caravans weighed more, it seemed logical to base tow ball loading on weight. Unfortunately, it is not. For truly long caravans, it is misleading.

Increasingly, one learns of caravan rollovers most of which involve longer caravans. Most occur whilst travelling fast. Many drivers subsequently commented: "The caravan had always seemed so stable until then".

This article attempts to explain what actually happens, why it happens, and what can be done to prevent, or least reduce the chances of one occurring.

Laws of Motion

Despite jack-knifings reported since the 1930s, tow ball loadings continue to be recommended as a percentage of trailer weight. They have been regarded as definitive, seemingly without anyone asking why. However, as basic physics, ongoing research and practical testing shows, it has no validity except for short caravans with centralised weight. Further, it is *impossible* to have validity as that contradicts the very basis of the fundamental Laws of Motion established by Newton as far back as 1687 and accepted ever since. In essence it overlooks that mass is not the same thing as weight.

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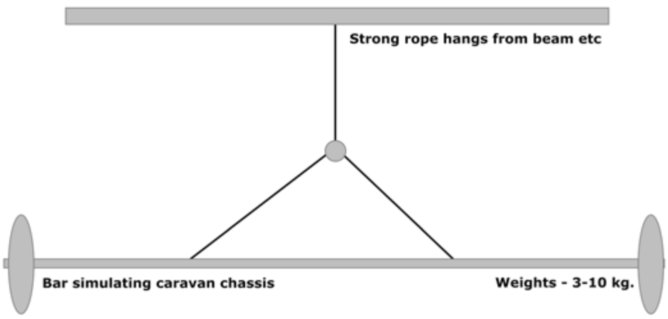
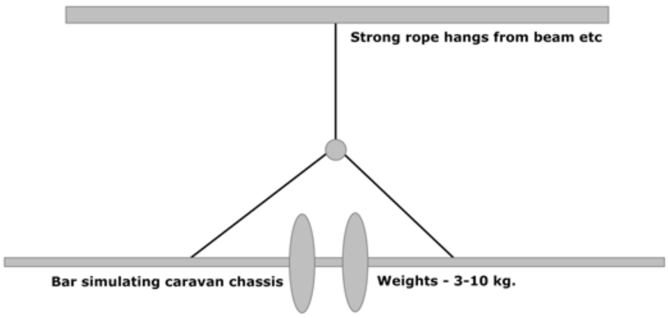
As shown (below) this is easily proved. Do the following, and it will be immediately obvious that the *effects* of weight on something like a caravan chassis are less related to the amount of that weight than to *where* such weight is located.



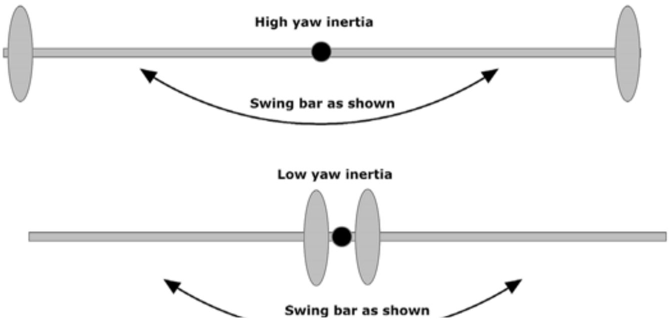


Find a longish bar - a broomstick will do. You will also need two weights (anything over about three kg will do) that can be fixed onto that bar (a body builder's weight set is ideal). That bar mimics a caravan's chassis.

With a strong rope in a Y shape as shown, hang that bar from some form of support. With no weights attached you can swivel that bar (pix below) with ease.

Placing the weights in the middle obviously makes it heavier, but it still swivels (although a bit less) easily.

You can stop it swivelling with similar minor effort.



Now move those weights to the ends of the bar. It still weighs the same, but is now much harder to swivel - and equally harder to stop.

Trying that with heavy weights may truly surprise. For a *truly* serious demo and closer to caravan yawing reality, (but making quite sure that bar is safe), test it with two 25 kg weights. Take care: once it's moving, trying to stop it may push you over!

Moving those same weights to different positions along that bar totally changes the force needed to swivel that bar, and to stop it moving once it does.

This dramatically illustrates the fundamental difference between mass and weight. The weight demonstrably remains the same, but its mass (and the effects of its mass) depends on *where* along the bar that weight is located. It shows that, for *exactly* the same weight, the effect of sway-inducing forces are *very* much greater on an end-heavy bar (chassis) than on a centre-heavy bar (chassis). It also shows that the longer the bar (chassis), the greater is this effect. It also shows that ensuring the weight is balanced end to end makes no difference to this effect.

Mass & Weight

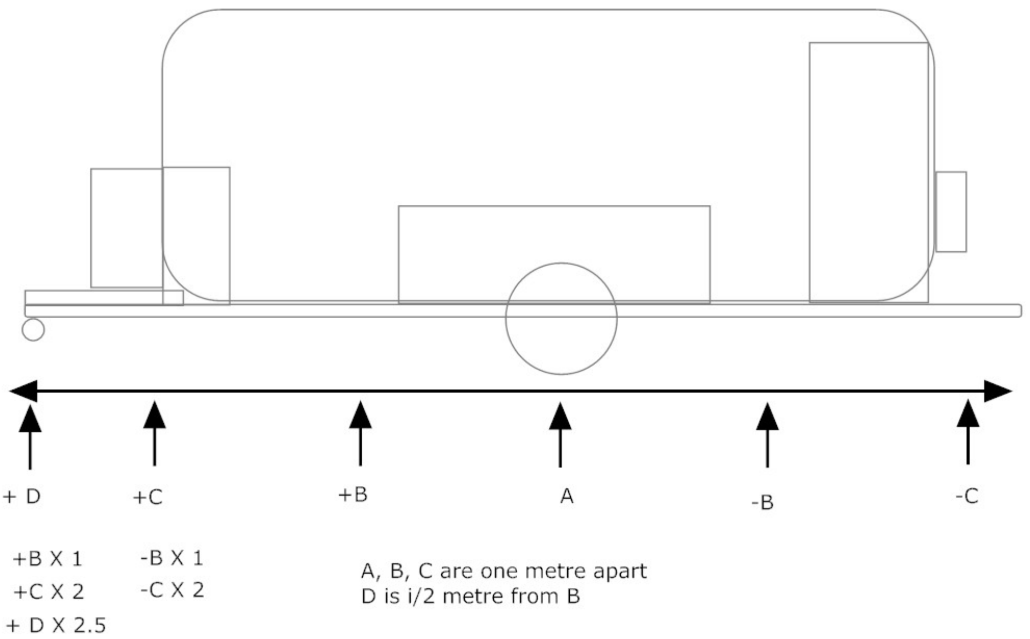
As shown above, mass and weight may seem two words for the same thing, but they are quite different concepts. The former is a measure of the amount of material in something. It *remains the same* no matter where it is. Weight is the effect that the force of *gravity* has on mass: i.e. it pulls mass downward.

To say that a certain mass weighs (say) 10 kg is only about what it would weigh on Earth. In space, a mass is weightless but will, if thrown at you, hurt just as much because its weight is still equivalent to that on Earth. For many purposes, mass and weight can be seen as the same thing. However whilst'weight' is fine for matters like cooking, it is not the same thing at all with matter that moves. With those, mass is generally the relevant concept.

All mass resists moving. It requires an external force to act upon it to do so. Once moving, mass continues in a straight line unless an opposite force opposes it doing so, or deflects it in another direction. Played billiard balls are a very good example; so is a caravan bowling down Prince's Highway at 100 km/h, a module travelling in space, and a car ferry at sea.

The above effect is called 'inertia'. Purists may prefer to define it as 'that property of matter that presents resistance to any change in the momentum of a body' (momentum is the product of mass and velocity - thus a mass at rest has zero momentum). The resistance to that mass being partially rotated, as when a caravan sways, is called yaw inertia.

What that bar experiment shows (if you'd actually measured the forces) is that the effect of mass of any given weight along that bar increases arithmetically by its distance from its pivot. The mass of 100 kg in weight, two metres in front of/behind a caravan axle has an effective weight equivalent to 200 kg. At four metres it is 400 kg. That's why the bar becomes harder to start swivelling, and to then stop swivelling the further those weights are from its centre.



Th*e* ***effect*** *of adding weight is related to where along the bar (chassis) such weight is located. In the sketch above (of a typical five metre 'van), 200 kg at -+B and -B becomes an effective 500 kg at +C and -C and about 600 kg at +D. This effect becomes of great importance for long end-heavy 'vans. Sketch (and copyright 2011): Caravan & Motorhome Books, Church Point, Sydney 2105.*

The forces associated with an accelerated mass (as in yawing and pitching) are proportional to the square of the rate of such acceleration. That is a further cause of the (end-loaded) bar being harder to start, and stop moving once started.

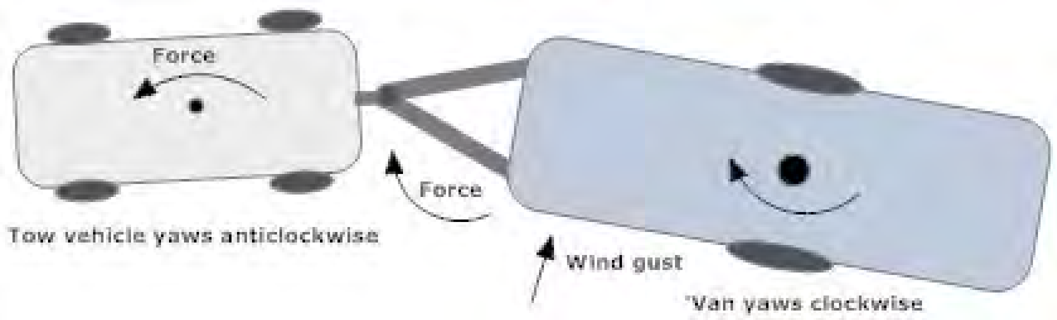
Yawing

A moving caravan's momentum causes it to continue in a straight line unless an external force deflects, slows, or stops it. But if (say) a wind gust deflects it, that force will cause the caravan to yaw and that yawing inertia can only be totally reacted by an equal and opposite force.

The only equal and opposite force available to provide that reaction is the tow vehicle's reluctance to have its mass shoved sideways (i.e. its *own* inertia), plus the frictional grip of its tyres' footprints on the road (not good on wet ones). If the caravan's yaw inertia *exceeds* the tow vehicle's ability to counteract it whilst travelling fast, jack-knifing is virtually inevitable.

Why rear-end mass is particularly bad is because there is no tow vehicle or any other mass at the rear that can react it. Adding mass there is like inviting a king brown into your kids' playroom. It is fine if not disturbed but it will bite if sufficiently provoked.

Inertia *assists* stability whilst the rig is travelling in a straight line on a straight road on a still day. Big rigs doing that not only feel ultra-stable, they *are* normally ultra-stable. But if anything that exerts a side force (e.g. wind, adverse camber, sudden swerve) sufficiently strong as to cause that caravan to yaw more strongly than the tow vehicle can react, the very same (and huge) mass that previously caused that caravan to seem so stable, is (like the king brown in the playroom) the *very same mass* that is now its undoing.



The yaw cycle. As the 'van yaws to the right, it causes the tow vehicle to turn to the left. The yaw forces are reacted by the inertia of the tow vehicle and ultimately by the lateral grip of its tyre's footprints. It then (hopefully) swings back to the centre, but 'overshoots'. The cycle repeats until the yaw energy is dissipated - mostly via tyre hysteresis and wind drag. Sketch: Caravan & Motorhome Books.

A caravan thus needs enough inertia to assist stability, but not such that it overwhelms; as with an arrow in flight, but without the aid of feathers to keep it straight. It is where heavy things are positioned *relative to the centre of the caravan's axle/s* (or more correctly its Centre of Mass) that determines the amount of yaw inertia. The further that distance, and the nearer to the trailer's sides, the greater will be the yaw inertia. A long end-heavy caravan has, because the effect of weight at its ends is affected by a so-called Moment Arm thus introduced, must *inherently* have more inertia than if that weight were more central. In addition, the longer the caravan the higher is its yaw inertia. Despite this, *none of the above,* and particularly the multiplying effect (the square law (of accelerating mass positioned at distance) has seemingly not been taken into account in tow ball weight recommendations for the past six decades.

Example 1
Two deep cycle batteries and gas cylinders on the drawbar of a four metre caravan weigh about 100 kg, but have mass of the weight equivalent of 200 kg. For an eight metre caravan that mass becomes the weight equivalent of 400 kg.

Example 2
A rear-mounted toolbox on an eight metre caravan may weigh 80 kg - but its mass is the weight equivalent of 320 kg. Yet there is nothing at that end to react it.

Caravans of similar length and weight but different mass distribution have very different yaw inertia. Both need front end mass for stability, but the effects of such mass in side winds etc will be very different.

Whatever that tow ball mass needed for stability, it can never be simply a percentage of overall weight (except for the short, centre-kitchen caravans, barely long enough to have excess yaw inertia anyway, which resulted in that original 7-10% of overall weight tow ball loading). Until recently however, it was not seemingly realised that nature's physical laws preclude it being relevant for longer trailers and especially if yawing and/or pitching. For shorter trailers that convention may be workable, but, as sanely loaded camper trailers demonstrate, that weight could be far less if desired.

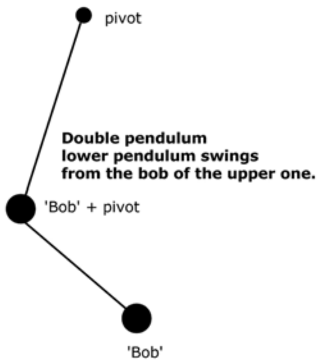
Following this false premise has probably masked the vital importance of low yaw inertia when towing a trailer suspended from an overhung hitch (a hitch that pivots behind the rear axle). It is becoming important now, as long end-heavy caravans become increasingly common in Australia and shorter lighter ones are being towed at very high speeds (particularly in Germany) by vehicles with the power to do so.

The Swing of the Pendulum

Yawing and its effects are *inherent* in any trailer suspended by a pivot located at a distance behind the tow vehicle's rear axle. It is thus not an issue with fifth wheelers.

If one hangs a fifth wheel caravan end-on, and it is then pushed sideways and released, it will swing just as does the pendulum on a grandfather clock: simply, predictably and controllably. It does much the same on road.

A conventional caravan behaves differently. Hung the same way, and such that the tow vehicle can swivel slightly, the caravan acts as a pendulum hung from the bob of a much shorter pendulum (that bob is the tow ball *behind* the rear axle of the tow vehicle). When the caravan pendulum swings, it causes the bob of the pendulum suspending it to move slightly by that force, and in the direction of that force. As it swings back, it causes that bob to move in the other direction. The two pendulums thus interact, but as one swings one way it causes the other to swing the other way.



A conventional caravan behaves like this double pendulum. As the upper one swings to the left, the lower one suspended as it is from the bob of the upper one, swings initially in the opposite direction but beyond a certain level of disturbance, movement becomes random and thus totally non-predictable. It is literally the physicists 'Chaotic behaviour'.

This: http://www.youtube.com/watch=mfLnLwFcSBc shows only too dramatically what happens next.

Also see: http://www.darkside.com.au/pendulum/index.html -

A user adjustable version that includes the maths and physics is at: http://www.myphysicslab.com/dbl_pendulum.html

Double pendulums never repeat the same pattern of movement twice. (Re the above, it is not clear from the instructions that, to restart after a 'reset' you move one or other bob with your mouse.)

The interaction is complex. Once beyond a certain level of disturbance, their ongoing behaviour, virtually in a split second, becomes random. It is *impossible* (practicably) to predict, and *impossible* to reverse. What may be clear in all of them is the violent movement of that bottom pendulum (the caravan) once they reach that chaotic state.

Further, that latter action is not repeatable, let alone predictable. Given the utmost care to replicate the initial conditions, and the elimination of *anything* that might affect it, the tiniest of differences (possibly even at atomic level) in the initial state results in hugely different results each time.

It is sometimes said that the beating of a butterfly's wing may trigger a cyclone (another chaotic phenomenon). The 2011 suicide of just one Tunisian is likewise thought to have triggered revolutions in many Arab nations.

Note in particular, the reaction of that lower pendulum on the bob of the upper one - that can be regarded as the tow vehicle. In particular by trying various ratios of tow vehicle/caravan mass on can readily see the side forces imposed on the rear of that tow vehicle. Such interaction is a mathematician/physicist's delight - and a caravanner's worst nightmare. Anybody claiming to have successfully reversed jack-knifing (as opposed to violent swaying) was not in a jack-knifing situation. Once that tow vehicle and/or caravan slides, all is lost.

FOUCAULT'S PENDULUMS

For those interested in both literature and pendulums Alberto Ecco's book Foucault's Pendulum is a great, (albeit 631 page) sort of intellectual Western thriller that improbably talks about pendulums (single) throughout. It even includes one page showing the mathematics involved!

Critical Speed

Inertia, as with momentum, is inherent in any moving mass. Further, as with many things in nature, the associated forces follow also follow yet another square law. This one relates to speed. The *energy* associated with a moving mass (by virtue of it being accelerated to speed) is thus four times greater at 110 km/h than at 55 km/h (not twice).

Energy can only be turned from one form into another; it *cannot* be destroyed. That same amount of energy needed to accelerate that mass to that speed, over a probable several

CRITICAL SPEED

Inherent in the nature of the double pendulum - of which a caravan on an overhung hitch is an almost classsical example of a system that becomes unpredictable minutes, fuels any resultant accident, but that energy is now compressed in time. It releases over the second or two of intense negative acceleration of the crash, in the form of heat and noise.

It is now known beyond reasonable doubt that this energy (related to speed) acts to fuel the action of a swaying caravan, and catastrophically once that sway exceeds the ability of the tow vehicle to restrain (react) it. Once sway forces are fuelled by that huge kinetic energy (i.e. that energy that a body possesses because of its momentum - it is inherent in any moving mass) and begin to act on an already wildly swaying trailer, the behaviour is rapidly escalated: jack-knifing is then virtually inescapable and virtually instantaneous.

So far, no tests have been performed on long end-heavy trailers, but the above is clearly apparent with shorter trailers. However, there are indications that, for some trailers, the critical speed above which this *may* happen (not necessarily *does* happen - it requires a strong trigger for it to manifest) could be less than the current towing limit of 100 km/h.

Sway Limiters & WDHs

Sway limiters may assist to absorb yawing forces (in early such device that convert the ‘yaw energy’ into heat energy). Later units employ spring loaded cam, or ball and socket mechanisms that in effect direct the sway energy to the tow vehicle’s ability (or otherwise) to react it via its own inertia and tyre grip. However, there is a limit to that ability.

A thesis associated with the University of Bath’s tests suggests that if a sway limiter’s limits are exceeded, it may suddenly release yaw energy into an already overloaded situation. My own feeling is that sway limiters should be used *only* to reduce sway as such; not to enable the driver to increase the speed before which swaying commences. Further, by in effect ‘masking’ rather than assisting to correct the cause of swaying at source, may preclude owners from realising the rig has problems, until it is lying on its side.

I suspect the same may be true of the inbuilt ‘sway stabilising’ system provided in some 4WDs. I have yet to meet an owner who appreciates they are ultimately limited no more or less by that vehicle’s inertia and/or lateral tyre grip. But, as the latter approach the point where they suddenly slide, their slip angles have become so great that they will cause that tow vehicle to oversteer - thus introducing a positive feedback loop. (See the author’s *Vehicle Dynamics*, for a reasonably simple explanation.)

A WDH (weight distribution hitch) appears to play no *direct* role in yaw control/reduction but by transferring much of the tow ball loads off the tow vehicle’s rear tyres primarily back to that vehicle’s front tyres (and partially to the ‘van’s own tyres) this assists to restore the tow vehicle’s ultimately limited inherent ability to react yaw inertia.

Owners Can Assist

A caravan’s pitch and yaw inertia can be substantially reduced by *centralising* weight such as batteries, water tank/s, stored goods, and heavy personal effects. Remove that heavy toolbox and/or bicycles etc from the extreme rear. If they are rear-mounted, consider if you really do need *two* spare wheels (I have driven across Australia’s centre over ten times - and have only needed *one,* and then only on two of those trips). I suggest selling one - and if feasible, relocating the other underneath. Consider moving heavy end-located portables to the tow vehicle. Ideally choose a tow vehicle that is at least as heavy as your van - and with minimal hitch overhang.

It is necessary stress what a huge difference the mass distribution of the caravan will make to that critical speed at which irreversible jack-kniving occurs.

Whilst looking at fairly extreme examples, where (whilst maintaining a constant tow ball loading) the difference in speed where seriously worrying yawing sets in for a (say) a 5.0 metre long ‘van may be 20-25 km/h and disturbingly close to the the typical towing 100 km/h speed limit.

As, (in January 2012 at least) little is known about the amount of yaw inertia in long end-

once a critical disturbing side force is exceeded. It is suddenly triggered into an irreversible and totally non-predictable action.
The action is what physicists calls ‘Chaotic behaviour’.

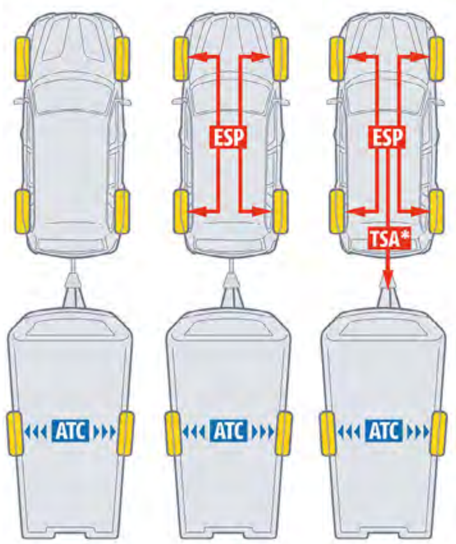
Amongst other factors that behaviour is now known to be speed- related, with the critical speed above which it may occur (given sufficient yaw-causing force) known to be specific to each rig (not just caravan) but also very much related to caravan length.

That speed, for long end-heavy ‘vans has not yet been trialled, but is believed to be close to the typical 100 km/h towing speed limit.
This is also covered later in the main text of this article.

heavy 'vans I seriously suggest keeping speed to no more than 90 km/h and far less when descending any steep gradient - where gravitational forces add to inertial forces once the 'van has started to yaw. (I need to add, for legal reasons, that I do not in the above in any way suggest that even 90 km/h is in any way a safe towing speed, excepting only that is less potentially risky than anything speed faster than that). Alternatively, to be free of all yawing action and its effects, choose the inherent stability of a fifth wheeler.

Technology May Assist

How the AL-KO system operates. In a detected emergency (only) the stabiliser instantly brakes both caravan wheels (not clear above), it first brakes the wheel ***opposite t****o the direction of sway harder than the other, thus pulling the 'van into line. Brake intensity is then increased and applied equally to* ***both*** *wheels as the rig straightens up. Pix: courtesy AL-KO Europe.*



The system can be used stand-alone: left and centre; or, if there is one, interfaced with the tow vehicle's own automatic stability system. Pix: courtesy AL-KO Europe.

AL-KO Europe has an 'emergency system' that detects road speed and the onset of swaying.If the 'violence' of swaying exceeds pre-determined levels, and the rig is travelling at what the system believes is too close to the critical speed (for that rig) it automatically, smoothly and progressively applies the trailer's brakes.

The unit brakes each wheel individually and in anti-phase with the sway, i.e. if the caravan's nose sways right, it brakes the left wheel, and vice versa. This not only dampens that sway, but also reduces speed, thus reducing the kinetic energy fuelling the action. The action is akin to a cyclone encountering cooler water, thus losing its source of energy and fading.

Above: unit being lifted into place. Right: in place Pix: courtesy AL-KO Europe.

This unit is already being used by Bailey Caravans in UK and others in Europe. So far it is suitable only for European type caravans under 1600 kg. It is not at yet known if it will be produced for trailers heavier than that (as even 1600 kg is considered heavy for European caravans).

It is an emergency-only auto-mobile 'air bag' safety approach operating for only a few seconds *before an* otherwise automatically assessed inevitable swaying chaotic transition.It does not control any other 'normal' trailer swaying.

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It has been proven effective, but only so far on European caravans that are already reasonably stable and with far less yaw inertia than typical of Australian trailers.

It is thus currently unclear if selective braking could react via the tyres the forces involved with a really long and end-heavy caravan swaying at high speed. The forces there are truly huge and my feeling is that they need tackling at source to reduce the probability rather than relying on a last-ditch emergency system.

Summary

The *amount* of inertia is a function of the total weight of the caravan. The *effect* of yaw inertia is related to where such weight is *distributed* in that caravan. Many interrelating issues affect stability, and not all can be foreseen (e.g. the inertia etc of the tow vehicle chosen, the length of its rear overhang), but guidelines assist:

Ideally, the trailer's weight should not exceed that of the tow vehicle. The tow vehicle should ideally have a long wheelbase, but short rear overhang.

It is becoming increasingly clear that a major villian is mass at the rear end. This is because, unlike the front - where the tow ball is connected to a vehicle with considerable inertia that to react yaw, the rear is only really restrained by the lateral, and that effective, grip of its tyres. Further, when descending a steep slope, there are additional (vectored there gravitational forces acting on the rear of the 'van once it has started to yaw.

Because of the above it is necessary to discourage people (including caravan builders) from adding extra mass - such as bicycles, heavy too boxes, spare wheels, fuel etc, and the heavy rear bumper bar itself.

Speed is a proven factor: the greater the yaw inertia, the lower the critical speed. That critical speed may well prove to be below the legal limit for high yaw-inertia caravans - or too close to that limit for comfort.

So far (UK) tests on shorter test trailers confirm that this is so. This problem mostly affects end-heavy caravans of a probably five metres and above (but also shorter caravans that are often towed at high speed on European motorways).

Except in extreme cases however, caravans up to a possible/probable five metres are at less risk, particularly if centre kitchen. They may yaw a bit, and that could overwhelm too light a tow vehicle, but that *critical* speed above which chaotic behaviour may be triggered is likely to be well above the towing speed limit. Its onset is thus less probable.

Design and materials need to be such that yaw inertia is minimised. This will be necessary anyway as cars and 4WDs generally are becoming lighter - and hence less able to react yaw inertia.

The further the pivot of that 'upper' bob (the tow ball) is behind the tow vehicle's axle, the greater the extent and severity of that snaking, and the lower the critical speed where chaotic behaviour can (not necessary *will*) be triggered. But all that is needed ito do that is for the disturbing forces that cause yaw inertia (fuelled also by the rig's momentum) to overwhelm the tow vehicle's ability to react it.

It is probably no coincidence that many recent caravan accidents involved semi-laden utilities with extensive rear overhang.

The most likely future scenario thus includes lighter constructional methods and materials, shorter caravans, a return to centre-kitchens, centrally-located batteries and tanks, a move away from gas (due to the mass of end-located cylinders, and their bulk), and toward diesel powered lightweight fuel cells. Rear mass will be rigidly minimised. Axles will be located further back.

Wind forces (including those generated by passing long trucks) also play a role. There needs to be more caravan side wall area in front of the axle than behind it - but that is achieved by the axle/s being located closer to the rear (desirable anyway). That also usefully reduces the yaw inertia of mass at the rear as that distance thus becomes shorter.

It will also be necessary to provide owners with sufficient information so that they do not load caravans in such a way as to negate the intent of reducing sway inertia -as for example one I saw some years ago - where the body builder owner stored half of his 500 kg or so of weights on the draw bar and the other half on a specially made rear bumper. No problem, he said, I worked it out so it all balances.

Tow Ball Loading

For on-road stability the caravan *must* be front heavy. If yaw inertia is low, it is likely that, over the range of 3.5-5.0 metres, 7% of overall weight is adequate. A (possibly) sliding scale of tow ball weight related to overall length is better as one based on overall weight is both meaningless and potentially dangerous.

Extreme ball loadings - this plus $750,000 5.5 tonne off-road 'van had a 1000 kg towball weight load. It was towed by this 5.5 litre twin turbo diesel Dodge Ram. It had almost unbelievably been taken extensively off-road and stayed for a few days on our then 10 acre property north of Broome. The 'van had developed cracks in its A-frame, was apparently nursed back to the East coast, repaired and then sold. Pix: 2009, courtesy Brian Fox.

These conclusions are likely to be contested by those not fully aware also of vehicle dynamics and in particular the concept of the now well-understood and documented of tyre 'slip angles', but experience is increasingly showing that most engineers and physicists accept all or most it. I do ask non-engineers (and any others not reasonably aware of Newton's First, Second and Third Laws of Motion etc) to first try that swivelling bar experiment.

That swivelling bar illustrates *in practice* the fundamental Laws of Motion involved - and their consequences. I probably should emphasise I am far from the only engineer arriving at the generality of the conclusions of this article. I seriously suggest the only way that the *generality* of this article can be seriously flawed is to render invalid some of those so far seemingly universal Laws - first set out (in Newton's Principia Mathematica in 1687) and accepted as valid (for general engineering purposes) ever since (except, of course by various internet forum posters who suggest it is 'all just another opinion').

(Further information on next page).

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Further Information

Vehicle Dynamics (www.caravanandmotorhomebooks.com)

The Dynamics of Towed Vehicles (http://people.bath.ac.uk/en8cjk/Caravan.pdf)

Chassis Design: Principles & Analysis - Milliken and Milliken (based on technical notes of Maurice Olley - who died in 1972, some 40 years before its publication).

Collyn Rivers can be usually contacted on 02 9192 1052 - during Sydney working hours.Caravan & Motorhome Books can be contacted on that same number.

The article is an updated version of the *Caravan World* edition. It has a different layout and photographs from my original article - that was published in the December 2011 edition of the December 2011 (Australian) magazine *Caravan World.* The magazine's very informative website is at www.caravanworld.com.au

A LINK to the *Caravan World* website , www.caravanworld.co.au is on the previous page, on our LINKS page, and can also be accessed via the LINKS button on our **HOME** page.

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