# The Role of Body Roll in Caravan Fishtailing

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## Abstract

During towing of a caravan or trailer it is not uncommon that the trailer sways back and forth as a result of steering input, crosswind or one of many other causes. Normally there is sufficient damping in the oscillations to realign the trailer with the tow vehicle. On some occasions the swaying enters an uncontrollable phase where the sway amplitude increases at each cycle. This paper examines the contribution of body roll of caravans to the out-of-control sway. The paper proposes resonance of fundamental body roll frequency with the sway frequency as a significant contributing factor. It also proposes that body roll can control sway amplitude helping to explain the out-of-control condition. There are some keys offered that may interest caravan manufacturers and caravan owners alike.

## Introduction

The aggregate mileage accrued by caravanners is growing rapidly world-wide. In the UK caravan parks saw turnover increase by 9% in 2016 according to research by Ortus Secured Finance. (Reporter, 2017) Meanwhile in Europe nearly 11% increase in Recreational Vehicle (RV) registrations was reported by the European Caravan Federation. (Clinch, 2017). The US saw an increase in RV sales of 17% over the previous year amounting to a total of $US 20 Billion in sales for the year. (RVIA, 2017).

Statistics for caravan fatalities or injury are typically buried under vehicular events and thus are difficult to extract. Nevertheless, the Federal Motor Carrier Safety Administration estimates some 75,000 people are hospitalized each year in the US. (Beebe & O'Neil, 2016).

In these growing statistics, the incidence of the fishtailing phenomenon would likely to be growing also.

When a fishtailing event is at the stage where the caravan controls the direction of the vehicle, it is probably too late for corrective intervention by the driver. Such a condition is beyond the scope of this paper which assumes a straight path for the hitchpoint.

A terminal fishtailing event goes through the following stages:

- A misalignment of vehicle centrelines caused by rapid steering input, wind gusts, overtaking or being overtaken, etc.
- A sway inwards to a realignment of vehicle centrelines at some cross-over speed.
- Overshooting the alignment to sway to the opposite side to some greater articulation angle.

- Return to the common centreline but at even greater cross-over speed.
- Swing to the next cycles of sway at ever-increasing momentum and articulation.

European Standard ISO 9815: 1992 sets out test procedures for caravan stability against sudden steering inputs. Amongst many other measurements, the angles between the prime mover and trailer are recorded as a compliance requirement. The Standard sets out a condition called ‘Zero Damping’ to delineate a zone below which recovery from fishtailing is likely. The Standard considers the zero damping as a sinusoid and the conditions below zero damping a decaying sinusoid.

Using the data provided by this Standard, typical damping and zero damping curves are drawn. Superimposed is a negative damping scenario representing the out-of-control condition.

This is envisaged in **Figure 1**.

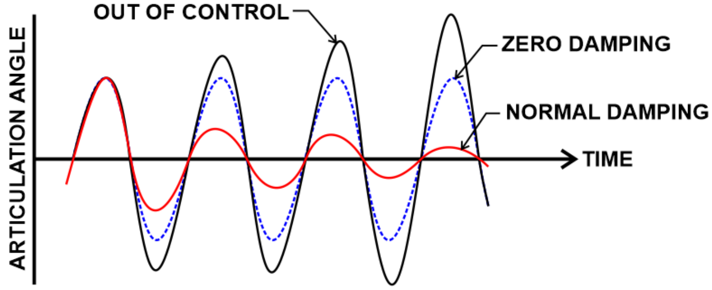



**Figure 1 – Articulation angles resulting from a sudden steering input.**

An out-of-control condition occurs when the articulation angle exceeds the zero damping condition. Many out-of-control videos can be found on the Internet. There is a sampling in **Table 1**.

Videos of real-world fishtailing events published on YouTube lend themselves to frame-by-frame analysis to extract very approximate fundamental vibration frequencies. These are also posted to **Table 1** with the overriding assumption that the frame rate of the videos was faithful to real time.

**Table 1 – Links to caravans fishtailing videos & their frequencies**

| Item | Video Link | Hz | Half-Period* |
|---|---|---|---|
| 1 | https://www.youtube.com/watch?v=HmH-gQYRYOU | 0.7 | 0.7s |
| 2 | https://www.youtube.com/watch?v=9RdojoXyBLg | 0.5 | 1.0s |
| 3 | https://www.youtube.com/watch?v=ApuLNMPFriU | 1.0 | 0.5s |
| 4 | https://www.youtube.com/watch?v=_ix7ZgsWTMg | 0.5 | 1.0s |
| 5 | https://www.youtube.com/watch?v=KxaK6It5WEk | 1.0 | 0.5s |
| 6 | https://www.youtube.com/watch?v=e3uuzI1jExY | 0.5 | 1.0s |
| 7 | https://www.youtube.com/watch?v=G_mYqCaaBdU | 1.0 | 0.5s |
| 8 | https://www.youtube.com/watch?v=FDqiR1wOAg8 | 0.7 | 0.7s |

*To the first decimal point

A half-period is the length of time to sway from one side to the other. These frequencies will later be compared with measured body roll vibration frequencies.

A theme throughout the above videos is the speed of the overall event from mild oscillation to overturning with some incidents taking only 4 to 5 oscillations. Also notable are the front wheels being straight throughout the oscillations suggesting no direct steering intervention took place. Some attempted to brake as can be seen by the illumination of brake lights. All suffered the terminal end.

On the ingoing side of the oscillation the driving forces are air/caravan interaction (windage), centrifugal action and the influence of the tractrix curve. The damping action comes from the lateral force on the tyres. On the outgoing side the driving force is the angular momentum acquired from the ingoing phase. The angular momentum is acquitted against the lateral force on the tyres and windage. The same windage from the ingoing phase is now seen as a damping force. At zero damping all these actions balance out.

Out of the experience of their comprehensive modelling, Sharp & Fernandez (2002) remind us: *"It is clear that any model that excludes rolling freedoms cannot predict such a mode with any detailed accuracy."* Central to this paper are the effects of body roll.

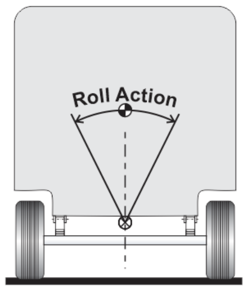
## Body Roll

Caravan body roll is best represented by a mass on a spring. When pushed in a particular direction energy is stored in the spring to be released when the force of the push is released. The mass will accelerate in a direction opposite to the direction of the push, i.e. simple harmonic motion. Dixon (2007) concurs: *"The roll mode of vibration is largely independent of pitch and heave and can be approximately assessed as an independent 1-Degree-Of-Freedom of (1-DOF) motion."*

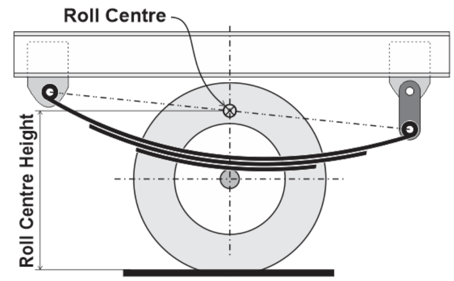
A high-school physics book will explain that the distance of the push will equal the rebound distance while the period of the oscillation will remain the same even though the amplitude will decay because of windage friction and spring material hysteresis. The period is an important parameter in this paper as the time for one caravan body roll oscillation can be greater than the time of a single sway from one side to the other. Whilst a 1-DOF is a good approximation for body roll it must be remembered that it is merely a simplification for potentially many degrees of freedom. For example, if the crockery and appliances spill out from overhead cabinets onto the floor during an oscillation event, the mass does not change but the roll dynamic will change as distance to the centre of mass from the roll centre will have changed.

Body roll is caused by lateral tyre resistance against the angular momentum of the caravan. The roll centre is a point about which the caravan rolls at any instant. This point can be determined for a caravan by the Aronhold-Kennedy theorem of three centres: *"When three bodies move relative to one another they have three instantaneous centres all of which lie on the same straight line."* (Barton & Fieldhouse, 2018). The theorem resolves to position the roll centres for two main types of suspensions in

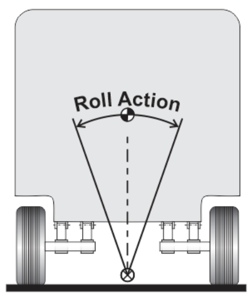
**Figure 2**.




**End View – Leaf Spring Suspension**




**Side View – Leaf Spring Suspension**




**End View – Trailing Arm Suspension**


**Side View – Trailing Arm Suspension**

**Figure 2 – Positions of roll centres.**

Most caravans are configured and loaded so that the mass is forward of the wheels. The roll centre then lies on a line between the roll centres in

**Figure 2** and the hitchpoint. This line is referred to in the literature as the roll line.

Caravan mass above the spring system (sprung mass) is important in the configuration of the 1-DOF spring system, best illustrated by the classic natural frequency equation (Blevins, 2016):

$$\omega_n = \sqrt{k/_M} \qquad [1]$$

Thus if the spring stiffness *(k)* increases so does the natural frequency. Conversely if the mass *(M)* increases the natural frequency decreases. Now the time *($T=1/\omega_n$)* for one sinusoidal period is often a preferred descriptor and can be combined with Equation [1], as follows:

$$T_n = 1/\sqrt{k/M} \qquad [2]$$

So that as mass increases, the period of the oscillation increases too. The implications here are to keep the mass of loading and the vehicle mass low (and the spring rate high) to maintain a shorter period (higher frequency) than the sway period; a necessary condition to avoid potential resonance.

## Body Roll and Sway Interaction

Understanding how body roll interacts with sway is essential to understanding the whole phenomenon. So that we can visualize the process simply, we build a Projection Plane as if a camera was placed on the back of the caravan. So instead of a curved path of the caravan sway we would observe a planar left and right motion. The idea is embodied in **Figure 3**.

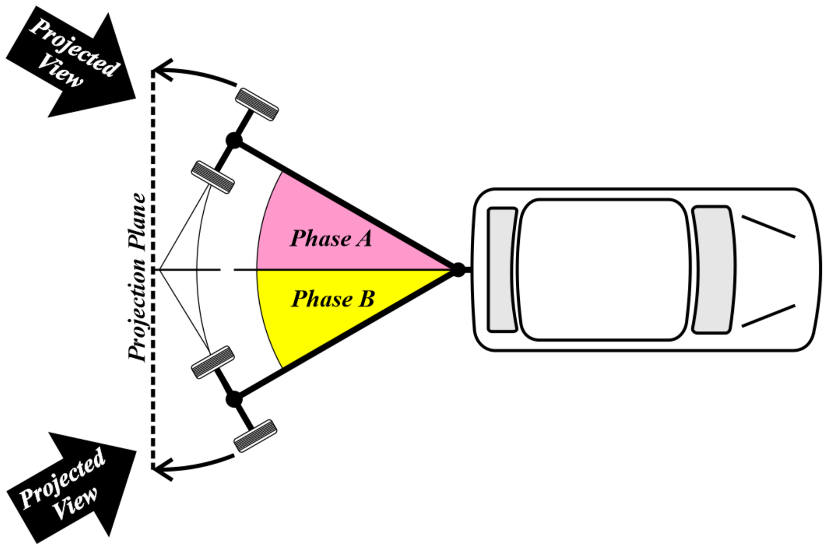



**Figure 3 – Concept of image projection showing oscillation phases.**

This idea is further expanded in **Figure 4** where the left and right caravan pictures mark the extremity of articulation and where the lateral velocity is zero.

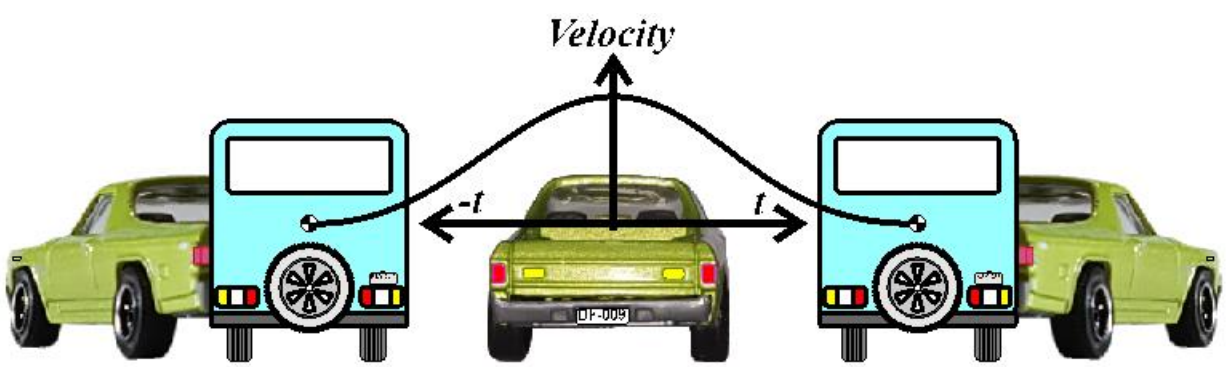
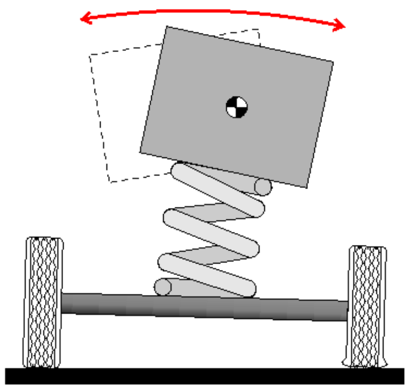



**Figure 4 – Image projection highlighting peak cross-over velocity.**

A sway from left to right will have a number of cycles of body roll where the body roll stiffness is high such as one might find on a caravan fitted with torsion anti-roll bar (often called stabilizer bar). This idea is embodied in **Figure 5**.



Body Roll
Including Tyre Deflection

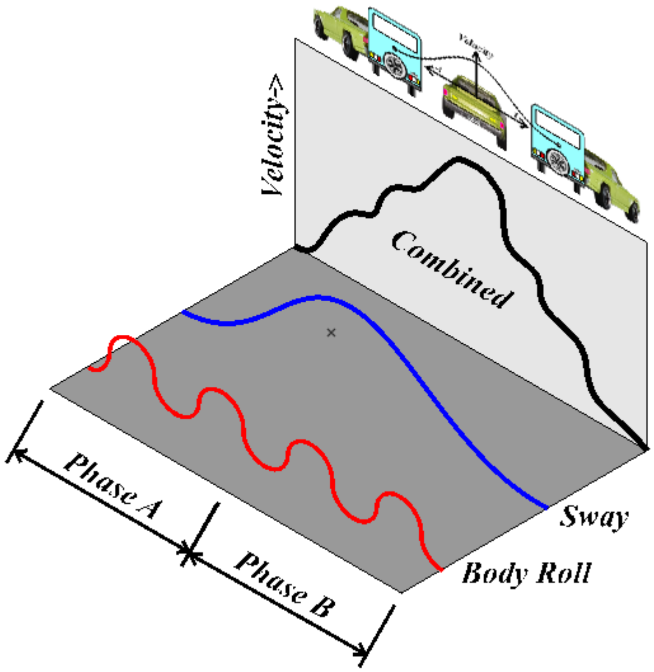



**Figure 5 – Visualization of combined body roll and transverse sway velocity.**

The body roll frequency shown in **Figure 5** is illustrative of a system fitted with an anti-roll bar. Anti-roll bars fitted as typically shown in **Figure 6** will increase the roll stiffness substantially. (Agrawal & Gustafson, 2017)

Anti-roll bars (as distinct from hitch area anti-sway bars and load levellers) are typically not fitted to caravans as part and parcel of normal supply. However, one manufacturer offers an anti-roll bar as an optional extra (Kimberley, 2014). Another manufacturer offers such a bar as a retrofit. (Cruisemaster)

A fitted Cruisemaster™ anti-roll bar is shown annotated in **Figure 6**.

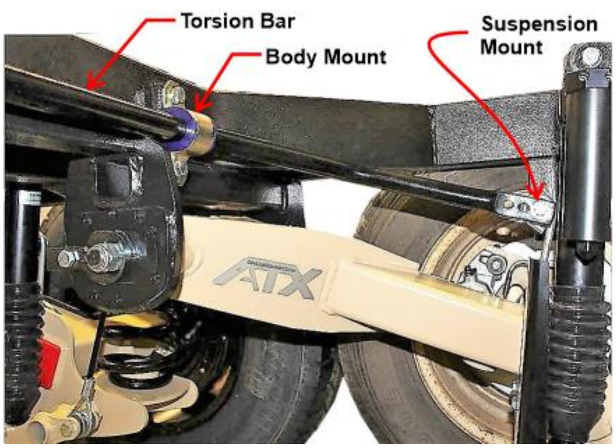



**Figure 6 – Cruisemaster™ torsion anti-roll bar.**

## Resonance

Resonance can be defined as:

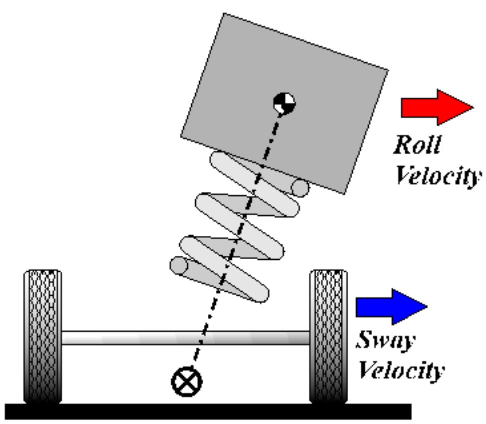
> *A system will oscillate at a greater amplitude when a periodic force is applied at a frequency near or at the system natural frequency. The system is said to be in resonance with the periodic force.*

The science of resonance came to maturity with the study of the Tacoma Narrows Bridge which failed in 1940 due to aeroelastic flutter at a mere wind speed of 68 km/h. The legacy of this catastrophic failure is now reflected in many engineering designs. Perhaps the most visible are smoke stacks with spiral fins to defeat vortex shedding.

Relevant note from Darling & Standen (2001) observing that a caravan would have a vortex shedding frequency of about 0.75 Hz being close to its yaw frequency and so risk self-excitation.

An oscillating mass such as shown in **Figure 5** will continue its path until its energy is expended. The peak displacement left or right corresponds to zero lateral velocity at that instant. If we accept the argument put by Dixon (2007) that body roll can be approximated by a 1-DOF system, it would be difficult to imagine that sway motion could control body roll if the body roll natural period was greater than the sway period.

The velocity curve from **Figure 4** is added to **Figure 7** and referred to as the "Sway Half-Period". In this scenario the body roll period is longer than the sway half-period. Given that body roll is about rotation of an arm to the roll centre, the peak velocity becomes the sway velocity plus the roll lateral velocity. This is visualized in **Figure 7** where the roll & sway velocities are notionally decoupled then combined.




**Sway & Roll Velocities Decoupled**

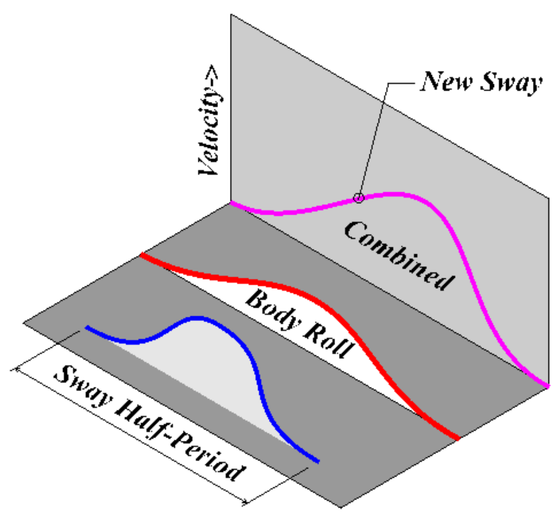



**Figure 7 – Visualization of long body roll half-period.**

If the body roll half-period were equal to the sway half-period, it could be argued the system was in resonance. **Figure 7** illustrates that successive sways can increase in cases of long body roll periods.

## Measuring Body Roll Angles

Measuring body roll angles is not an easy task on an instrumented caravan about to be destroyed. It would be an expensive undertaking and expose a driver of the towing vehicle to unacceptable risk of injury, possibly death.

Fortunately the authors have developed a method that provides an approximate body roll angle and cycle times of the oscillations.

The procedure is to select and capture video frames from dashcam videos that represent cusps where the caravan starts to sway in the opposite direction. On a frame-grabbed picture, a rectilinear line or object is selected and the outline is traced. Then a subsequent frame from an opposite cusp is selected and the same line or object is traced at the new position. The process is repeated whilst reversal of articulations offers reasonably normal views of the tracings. The process assumes the frame rate of the camera is faithful to real time.

Seven video frames of the back window from the caravan designated as Item 7 from **Table 1**, were selected and tracked at the left and right cusps and shown in **Figure 8**. The results are posted to **Table 2**.

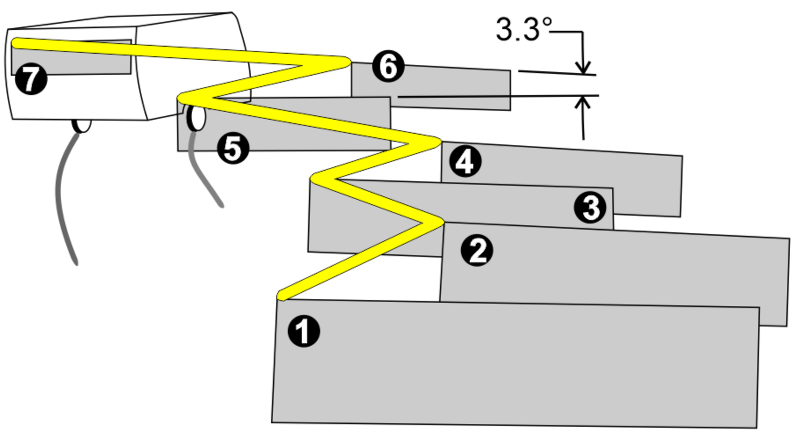



**Figure 8 – Study of window progression of caravan video #7 in Table 2.**

The angle of the window in Cusp #7 with the dashcam position precluded getting a realistic body roll angle. Cusp #5 is the last of the normal views making $6.0^{O}$ a better estimate for Cusp #5 to #6 roll angle, the normal being divergent to the dashcam line of sight.

The angle measured between Cusp #1 and #2 still reflects the windage from overtaking as the caravan came into view of the dashcam.

The skid marks have been faithfully reproduced on **Figure 8**. They indicate tyre slip saturation.

**Table 2 – Time study of Item 7 video in Table 2 measuring roll angles**

| Cusp | Oscillation | Time (ms) | Step (ms) | Cusp Step | Roll Angle |
|---|---|---|---|---|---|
| #1 | Left | 1 | | | |
| #2 | Right | 21 | | #1 to #2 | $1.7^{O}$ |
| #3 | Left | 1012 | 991 | #2 to #3 | $1.1^{O}$ |
| #4 | Right | 2004 | 992 | #3 to #4 | $1.8^{O}$ |
| #5 | Left | 3002 | 998 | #4 to #5 | $3.8^{O}$ |
| #6 | Right | 4000 | 998 | #5 to #6 | $3.3^{O}$ |
| #7 | Left | 5010 | 1010 | #6 to #7 | Bad view angle |

Worthy of note is the constant cycle time from cusp to cusp of nominally 1.0 seconds. The constancy is consistent with data from the European Standard ISO 9815: 1992 as set out in **Figure 1**. Fratila (1994) too, found that the oscillation frequency is more or less constant. He also found that the frequency to be independent of forward speed.

## Caravan Roll Frequency

The inputs required to determine the undamped fundamental body roll frequency are angular spring rates, height of caravan mass, roll centre height and tyre spring rates. Most of these are not available from manufacturers. Fortunately, caravan roll frequency is readily available by the gentle rocking of a physical caravan. Kratzman Caravans graciously gave permission for the authors to do that. The results are posted in **Table 3**.

**Table 3 – Fundamental body roll frequency tests for some caravans**

| Test | Make & Model | Size (L x H) | Suspension | Frequency | Half Period* |
|---|---|---|---|---|---|
| 1 | Aura Explorer | 5.4 x 2.8 m | Independent - single | 1.0 Hz | 0.5s |
| 2 | Aura Titanium | 5.4 x 2.7 m | Leaf Spring - single | 1.5 Hz | 0.3s |
| 3 | Goldstream | 5.5 x 2.4 m | Independent - single | 0.9 Hz | 0.6s |
| 4 | Jurgen Jinda | 5.4 x 2.2 m | Independent - single | 1.7 Hz | 0.3s |
| 5 | Mossman | 6.8 x 2.7 m | Independent - tandem | 1.8 Hz | 0.3s |

*To the first decimal point

The half-period of the terminal fishtailing event considered in **Figure 8** was found to be approximately 0.5 seconds. If this caravan was configured similarly to Test 1 in **Table 3** then the fishtailing could be attributed to resonance.

It is worth noting that all the caravans in the tests of **Table 3** were fitted with shock absorbers (dampers) except Test #2. Even so, leaf springs have inherent damping. Decay from the initial rocking varied but ranged 3 to 6 cycles to stop.

## Effect of Shock Absorbers

The value of shock absorbers is well-known. Instead of bouncing like a basketball after a speed bump, the oscillations decay quickly so allowing vehicular control to be maintained. They achieve their service by converting motion energy into heat energy. In the trade-off between control and passenger comfort many variants of shock absorber designs emerged. Maintaining simplicity, we consider the most basic type of vehicle damper, as shown in **Figure 9** drawn from data by Farjoud *et al* (2012).

Here the piston passes oil from one volume from one side of the piston to the other side of the piston through a small orifice. The gas volume below the free piston compensates for the volume of the piston rod. The characteristic curve shows that the Rebound stroke provides a greater force than for the Bump stroke. In the mechanical-work-done – energy equivalence, the rebound stroke dissipates more energy than the bump stroke.

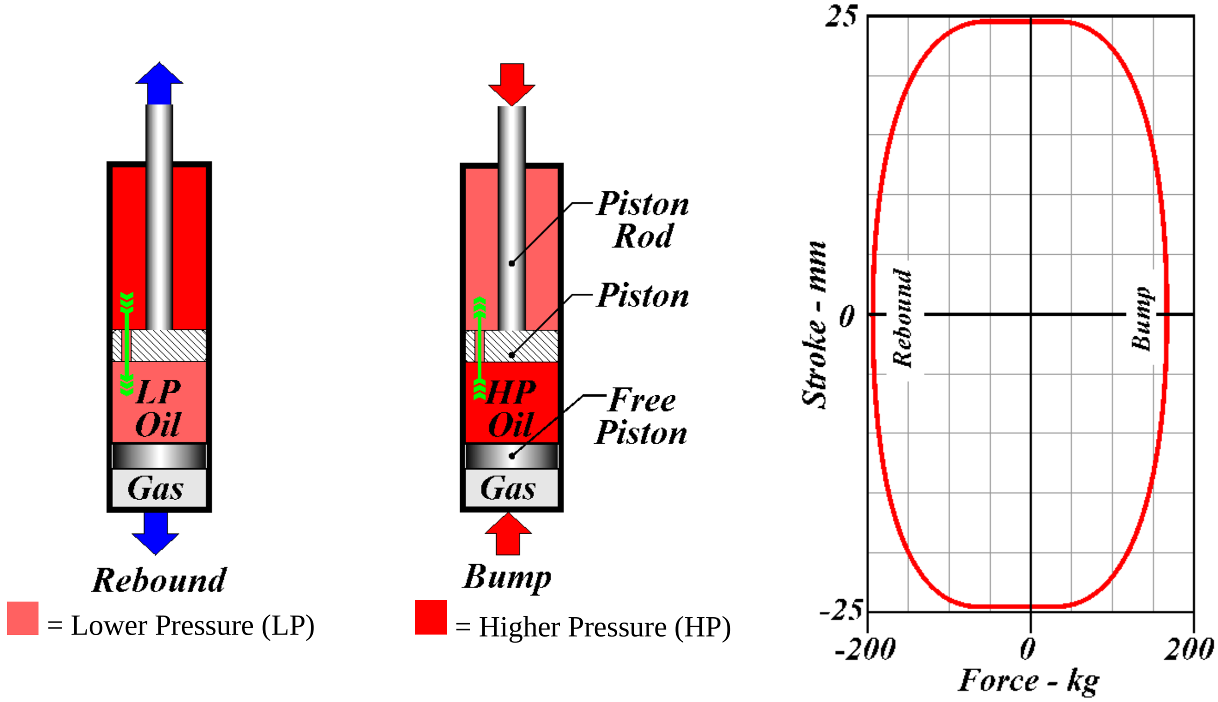



**Figure 9 – Simple shock absorber with typical characteristic curve.**

As the caravan rolls, the shock absorber on the down side of the roll moves first, being the bump side and offering less resistance. The shock absorber on the upside of the roll motion is in the rebound phase of its action.

Shock absorbers dissipate energy through a continual stroking. During a caravan roll event both shock absorbers stroke possibly only once during a long roll period. Little energy is dissipated from one stroke in each shock absorber. This is where anti-roll bars help, not only reducing the amount of roll but also offer more frequent stroking as shown in **Figure 5**.

## Conclusion

This paper set out to show that resonance of roll oscillations with sway frequency can be a contributor of the dreaded snaking or fishtailing of a caravan/trailer. This was achieved by physical tracing set features in frame-grabbed pictures from a dashcam video using drafting software, recording the time sequences of each picture. This provided the oscillation frequency for that caravan.

The oscillation frequency was compared to typical caravans for which the rocking cycle times were measured and recorded. It was found that two caravans so tested exhibited frequencies near or on the frequency for the dashcam video, so implicating resonance as the cause of that terminal snaking of that caravan.

Comparing cycle times of other dashcam caravans with measured cycle times of real caravans indicated that it is possible for roll natural cycle times to be greater than sway natural cycle times. This gave rise to the notion that body roll controls sway amplitude rather than resonance of the natural frequencies. Investigations of this potential phenomenon are continuing.

It was shown that shock absorbers (dampers) do little to reduce body roll amplitude on long body roll periods. Fortunately long body roll periods are easily reduced by adding anti-roll bars either as retrofits or routine fitment by caravan manufacturers. Both are highly recommended by the authors.

Whilst caravan loading involving hitchpoint loads is well covered in the popular literature, this paper identified absolute caravan mass of loading as a potential contributor to the fishtailing phenomenon, suggesting a reduced loading may decrease the risk of fishtailing.

## Declarations of Interest

None.

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