

# AIR SUSPENSIONS: DYNAMIC PERFORMANCE

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## ABSTRACT

In 1999 the author was requested to assist in evaluating a new air suspension developed by Bill Haire, Director of Haire Truck and Bus Repairs Pty Ltd.

Initial theoretical considerations by Lambert, and comparisons with standard trailing arm air suspensions revealed that the system had significant merit in overcoming air suspension deficiencies that had been described by drivers of “problem” prime movers as described in Lambert 2000.

“Problem vehicles” exhibit all or nearly all of:

- excessive whole body vibration at the drivers seat,
- excessive maintenance due to vibration related damage in the broad sense, c
- onstant steering input to control wandering, and
- the occurrence of significant divergences from the intended vehicle path without driver input (darting).

A risk assessment was undertaken and tests carried out that determined there were no increased operational risks with the new suspension, and that showed how other risks would be minimised.

Whole body vibration, excessive maintenance, wandering and darting have disappeared with fitting of the modified suspension; traction is comparable to mechanical six-rod suspensions; tyre wear is significantly reduced; and brake pad wear is even.

This led to further consideration of the theoretical reasons for these improvements, and these are discussed.

Comments are made about areas of poor design with other air suspensions, and recommendations made in respect of air suspension design. One recommendation arising from this evaluation is that air suspensions, whose design requires two height control vales to maintain the vehicle upright, should be banned on safety grounds. They result in a much increased likelihood of “problem vehicle” behaviour as well as loss of control and roll over, particularly on highly cambered roads.

## INTRODUCTION

In Australia there has been a massive move to air suspensions on heavy vehicles, largely brought about by the introduction in most states of extra axle mass for vehicles with road friendly air suspensions.

Prior to that time most suspensions were mechanical spring designs with load sharing functionality built in. Two mechanical spring designs are shown schematically below.

The load sharing mechanisms provided for high speed load transfer and hence at speed provided dynamic load sharing. With these suspensions most of the damping was achieved through interleaf friction combined with tyre hysteresis.

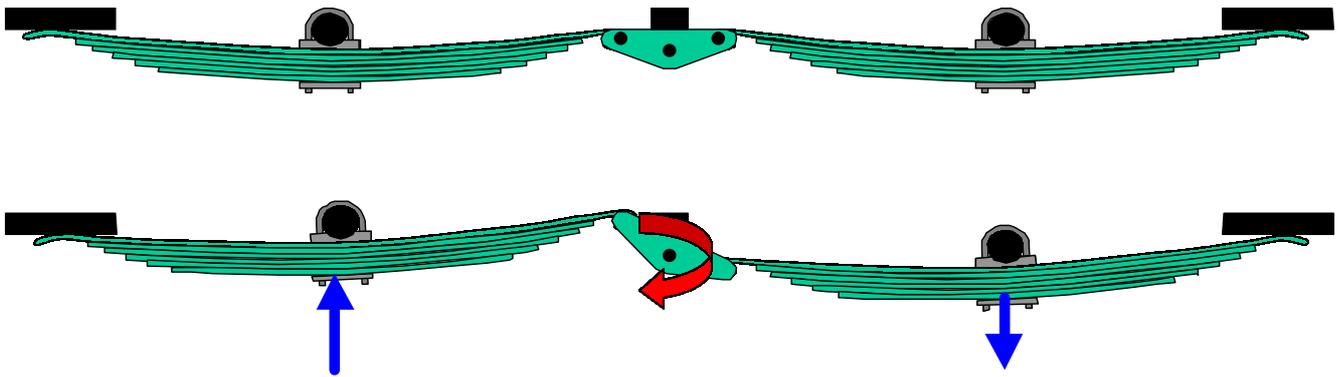


Figure 1. Trailer style bogie suspension with load sharing through a rocker arm.

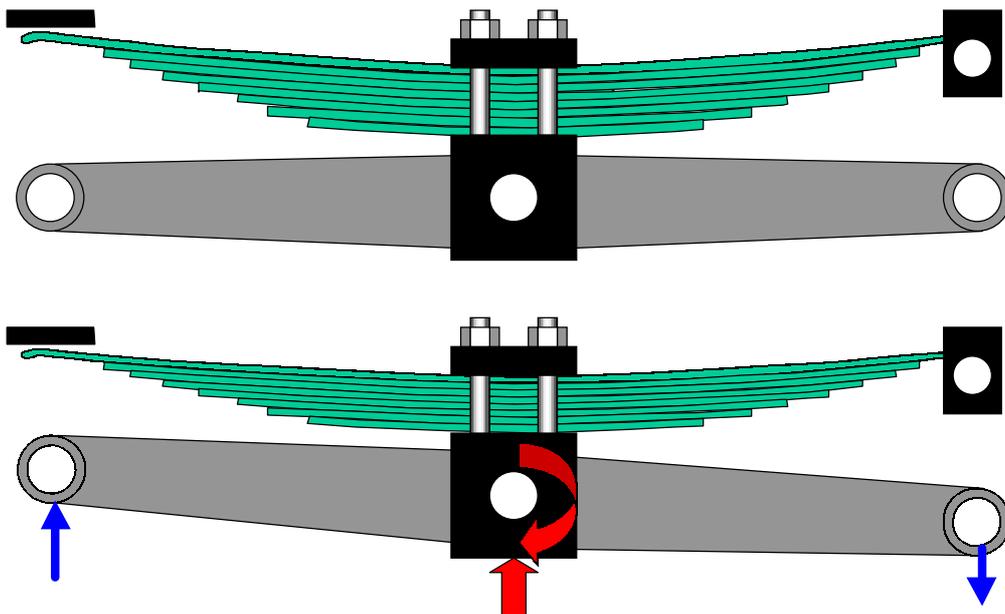


Figure 2. Bogie suspension with load sharing through a pivoted arm.

Air suspensions had been trialed on heavy freight vehicles in the 1970's but were abandoned for a number of reasons including the fact that freight vehicles tended to exhibit excessive roll from side to side.

During the 1980's and into the 1990's testing was undertaken to "prove" that new air suspension designs fitted with appropriate shock absorbers reduced pavement damage. For example Sweatman 1982. Much of the testing was done using pavement testing machinery similar to that shown below.

Almost all this equipment uses at most dual wheels on a suspension unit, and the majority of testing is at low speeds of 50 km/h or less. Units are of designs that generally do not allow the testing of complete axle group suspensions.

As far as the author can ascertain, in all the road friendly suspension testing there was only a limited amount of testing at 80 km/h and virtually no testing above this speed.

Hence there arises a question about whether air suspensions are road friendly at the speeds most trucks travel at on open roads. That is speeds of 90 km/h or greater.



Figure 3. Pavement testing machines.

## PROBLEM HEAVY VEHICLES

With the introduction of air suspended heavy vehicles, there was an apparent increase in the frequency of “problem” heavy vehicles.

“Problem heavy vehicles” exhibit all or nearly all of:

- excessive whole body vibration at the drivers seat,
- excessive maintenance due to vibration related damage in the broad sense,
- constant steering input to control wandering, and
- the occurrence of significant divergence from the intended vehicle path without driver input (darting).

The problems may be described as those that arise from chaotic behaviour of the prime mover – that is non-uniform and/or random periodic movements of the major components of the prime mover in relation to each other and the road pavement at frequencies ranging from less than 1 Hz to 70 Hz or greater.

These vehicles exhibit high levels of what can be broadly described as “vibration”

“Problem” heavy vehicles were primarily those with light torsionally flexible long chassis; raised heavy cabins and sleepers; large, high, and heavy high powered motors; torsionally rigid trailers carrying high COG loads at axle mass limits; and were vehicles which travelled on secondary highways at 100 km/h.

Owners of these vehicles commonly reported that the vehicles were fine up to 80 km/h. Lambert 2000 discusses these problem vehicles.

Work by the authors and Bill Haire of Haire Truck and Bus Repairs has shown that these problems can be eliminated by changes to the drive axle air suspension and corrections to poorly designed transmission shaft layouts.

This again raised questions about the current design of air suspensions as fitted to heavy vehicles.

## **FORS HEAVY VEHICLE SAFETY PROJECT**

This project attempted to determine the cause of the behaviour of the problem vehicles, including “wandering, poor handling, instability and abnormal vibration.” Eight trucks were heavily instrumented to record a large number of variables including air bag pressures.

Unfortunately only the rear drive axle air bag pressures were monitored.

Vehicles were operated on three sections of road as close to 100 km/h as was possible. The same test driver was used and he chose a speed that he was comfortable with given the vehicle’s handling and the road environment. And all vehicles towed the same flat bed trailer and the same load.

There were five “problem” vehicles tested (File F1, F3, F4, F6 and F26) and three bench mark vehicle supplied by manufacturers (BM1, BM2 and BM3).

As shown in Table 1 below and highlighted in yellow, mean air bag pressures as measured in the left and right airbags on the rear drive axle varied dramatically on three of the eight vehicles. In the worse case the ratio of airbag pressures was around 2:1.

Table 1. FORS heavy vehicle safety report – air bag pressure data.

File	Vehicle	Euroa (straight section)		Nagambie (winding) section	
		LH air bag pressure (psi) mean	RH air bag pressure (psi) mean	LH air bag pressure (psi) mean	RH air bag pressure (psi) mean
F1	Kenworth T900	59.5	59.7	59.3	59.6
F3	Kenworth C501	85.2	37.1	69.3	40.8
F4	Mack CH Fleetliner	49.6	53.5	49.3	53.1
F6	Ford LT 9513	74.6	54.4	72.5	54.9
F26	Mack CH Elite	53.3	54.0	52.9	53.6
BM1	Mack CH Fleetliner	53.7	53.1	53.1	52.4
BM2	Kenworth T900	69.6	51.4	68.3	52.5
BM3	Volvo NH	56.5	54.0	51.0	57.5

It should be noted that mean speeds were not always close to 100 km/h. As shown in Table 2 below, mean speeds varied significantly. On the straight section one vehicle had an average speed of only 84.7 km/h. And on the hilly section while two vehicles were able to maintain mean speeds close to 100 km/h, the rest had means that were much lower.

On Australian secondary highways there is generally a significant degree of camber present. As vehicles travel on the left hand side of the road, this camber will cause the mass on the left hand tyres to be around 5%-10% and up to 18% greater than that on the right hand tyres.

Analysis of moments and forces requires that for the same location of the vehicle’s centre of mass, the load through the tyres remains the same, even if the air bag pressures vary dramatically. Hence the forces generated by the unequal air bag pressures above are largely redistributed through torsion in the axle, and the net effect of the unequal pressures is to distort the suspension, Due to roll steer effects on trailing arm air bag suspensions, the end result is that the axle is effectively dynamically misaligned leading to all the problems associated with a misaligned drive suspension.

Table 2. FORS heavy vehicle safety report – speed data.

File	Vehicle	Speed Euroa section mean (km/h)	Speed Nagambie section mean (km/h)
F1	Kenworth T900	96.4	96.4
F3	Kenworth C501	Na	88.1
F4	Mack CH Fleetliner	Na	Na
F6	Ford LT 9513	98.5	95.6
F26	Mack CH Elite	97.9	83.8
BM1	Mack CH Fleetliner	84.7	88.7
BM2	Kenworth T900	92.8	91.6
BM3	Volvo NH	96.5	88.9

Modelling by Lambert of airbag pressures versus forces and the mass distribution across the vehicle axle groups also suggests that the average airbag pressures at the rear drive axle may be up to 10% higher than expected for the load carried. This will have the effect of transferring load onto the steer axle, a phenomenon reported by the drivers of these vehicles as “it feels like the rear air bags have jacked up.”

But what causes this unequal pressure?

### CURRENT AIR SUSPENSION DESIGNS

A typical design is shown schematically below.

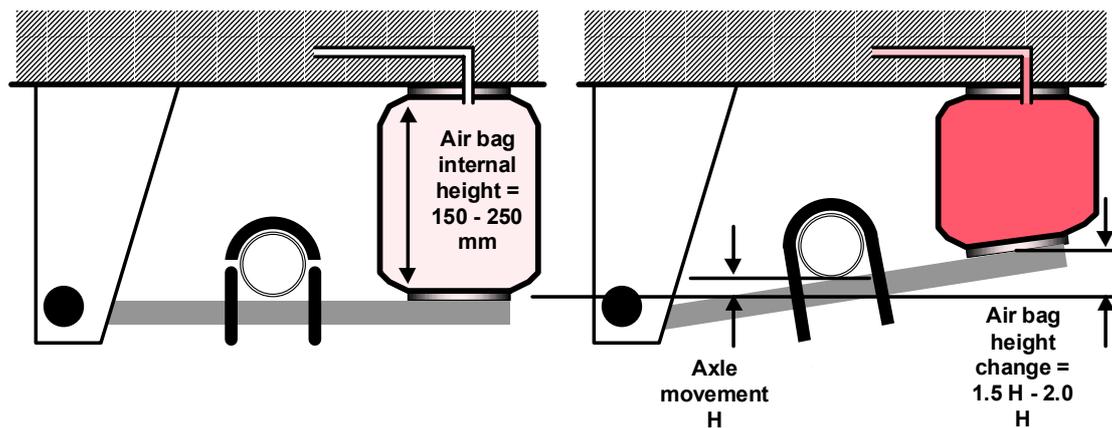


Figure 4. Typical air suspension – shock absorbers not shown.

Because of the geometry of these units, the air bag height changes by 1.5 – 2.0 times the change in height of the axle.

Typically the connections between the air bags are small-bore tubes with sharp edges orifices into the airbags.

However airbag suspensions also incorporate a height control valve (HCV) or valves aimed at ensuring the correct ride height of the vehicle so that geometry of the vehicle is maintained regardless of the load. The basic arrangement is shown below.

The HCV is actuated typically by a rod from the valve lever to the rear of the trailing arm on the rear axle.

When a load is placed on a truck the trailing arm rises and the HCV acts to pressurise the air bags until the vehicle height returns to its set height. Conversely when a load is removed the HCV acts to exhaust air from the air bag to atmosphere.

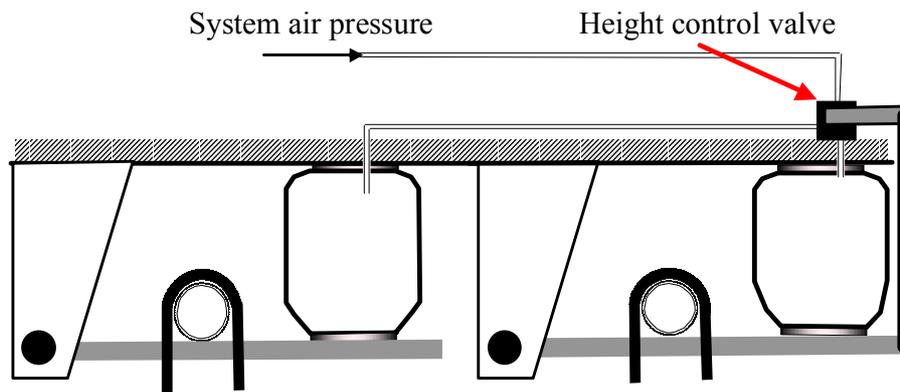


Figure 5. Bogie air suspension with height control valve – neutral position.

However the HCV also acts during travel as the vehicle travels over roads that are uneven. As shown below when the rear axle goes over a bump the HCV acts to put air into the rear air bag. Because the tube length to the rear airbag is small, air will flow more freely into this bag compared to the front air bag that has a much longer tube length.

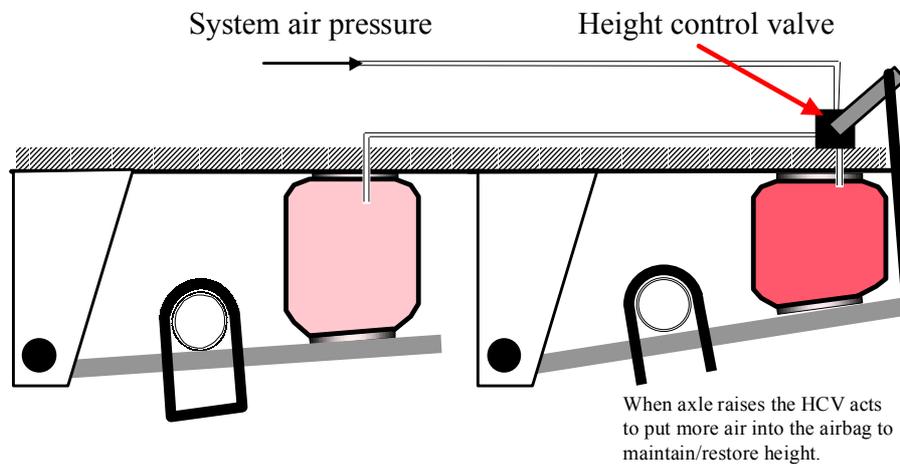


Figure 6. Bogie air suspension with height control valve – rear axle raised.

And if the rear axle drops into a depression the HCV acts to exhaust air from the rear airbag. And the air will move more freely out of the rear air bag.

The net effect of the movement of the HCV with the vehicle travelling at speed depends on the sensitivity and design of the HCV, the location of the HCV, the system air pressure versus the airbag pressure, and the geometry of the tubes connecting the airbags. Unless all connections to the airbags are of equal length and with the same air line fittings, there will be a tendency for the air bag pressures to change until the net flow into and out of all the airbags is the same.

With some suspension designs with a lot of compliance, two HCV's are used to maintain the truck upright. Where two HCV's are used, one on each side, the effect of road camber is to cause the vehicle to lean in the direction of the camber (toward the low side). In Australia, with sensitive HCV's the left bag will be pressurised and the right bag depressurised. This is the case with all the vehicles above where there is a large difference in air bag pressures from left to right.

In summary, the HCV changes the suspension from a passive suspension to an active suspension, and that can lead to significant problems in handling as a result of significant variations in air bag pressures.

## CURRENT AIR SUSPENSION DESIGNS – DYNAMIC LOAD SHARING AND DAMPING

In order for airbag suspensions to load share, air must be transferred from airbag to airbag with each bump or depression. However the small bore size of almost all current designs prevents the transfer of large amounts of air.

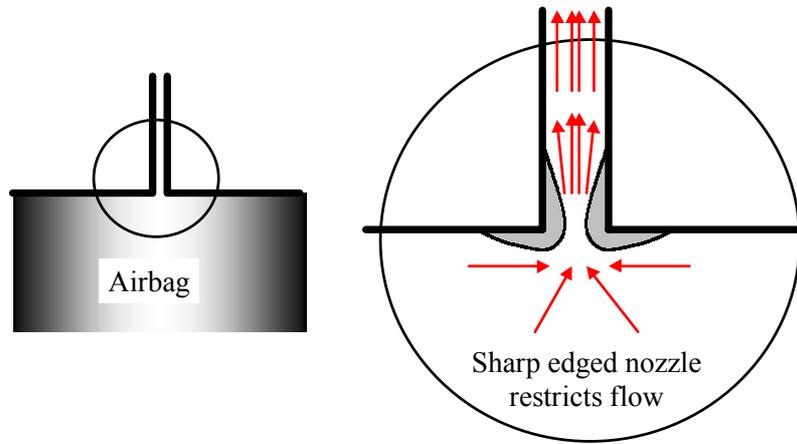


Figure 7. Effect of sharp edged tube connection to the air bag.

Further connections of these tubes to the airbags generally generate sharp edged orifices as shown above. These act to further restrict flow, possibly by as much as 50%.

As a result in a high speed environment the airbag acts as though it is blanked off and there is no dynamic load sharing.

The flow of air to and from an airbag generates turbulence, and hence energy loss as heat. This energy loss acts to dampen oscillations. The concept is shown below.

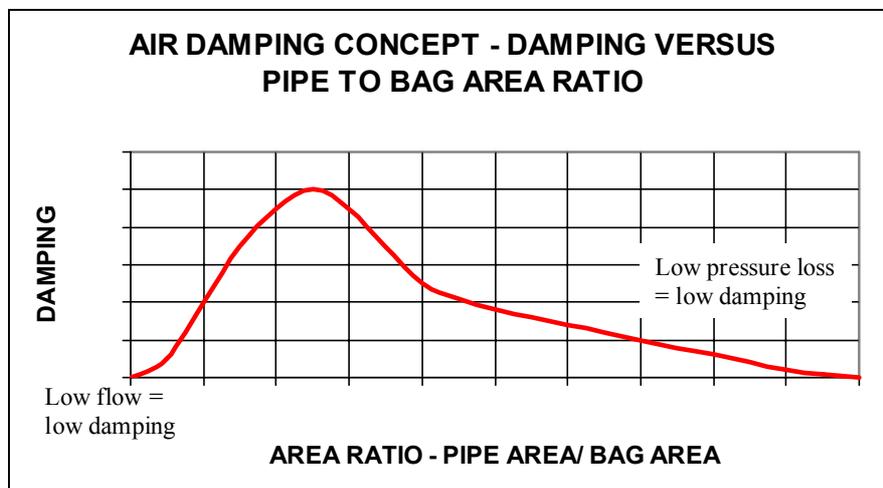


Figure 8. Concept of air suspension internal damping.

For small bore tubing there is little airflow, hence the internal damping effect is low. Conversely for very large tubes there is little turbulence generated because there is only a low pressure drop. Hence at some intermediate point maximum damping through air bag to air bag flow is achieved.

## INNOVATIVE DYNAMIC LOAD SHARING AIR SUSPENSION

Haire Truck and Bus Repairs over the past 10 or more years has developed an air suspension system that tends to correct all these adverse behaviours.

The system consists of:

- Large diameter (50.8 mm) orifice transmission lines with biased airflow control to achieve fast response and optimal load sharing between axles in an axle group,
- Relatively large diameter pipes (20 mm) from the air bag to the transmission lines;
- Detailed design features that generate around 7% damping through internal air flow; and
- Innovative mean ride height feedback linkage to generate correct feedback signal without the HCV actuating with every bump or depression



Figure 9. Large diameter orifice transmission line.

Figure 9 shows the fittings for one side of a tri-axle group. An appropriate length of 50.8 mm hose is fitted between the fittings shown.

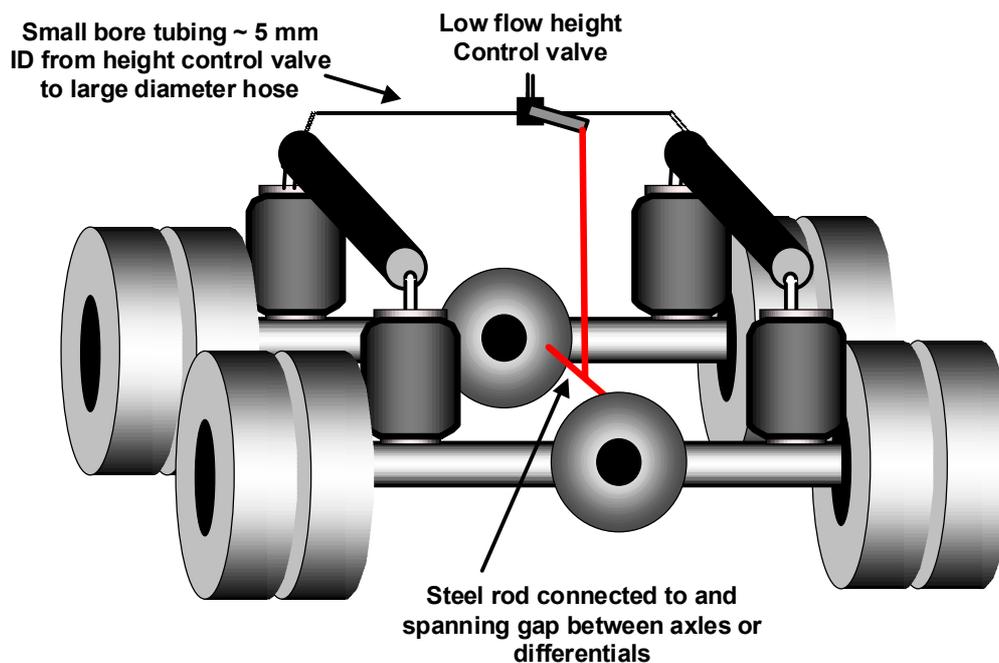


Figure 10. Mean ride height feedback linkage.

A system of rods is used to sense the mean height of a bogie axle group as shown in Figure 10. For a tri-axle group sensing the centre of the centre axle may suffice. As a result of the limited degree of actuation of the HCV air consumption is dramatically reduced.

In McLean et al (2003) the change in airbag pressure in response to a step input was calculated with the results shown below. The figures assume both wheels on an axle negotiate the same 100 mm step at the same time.

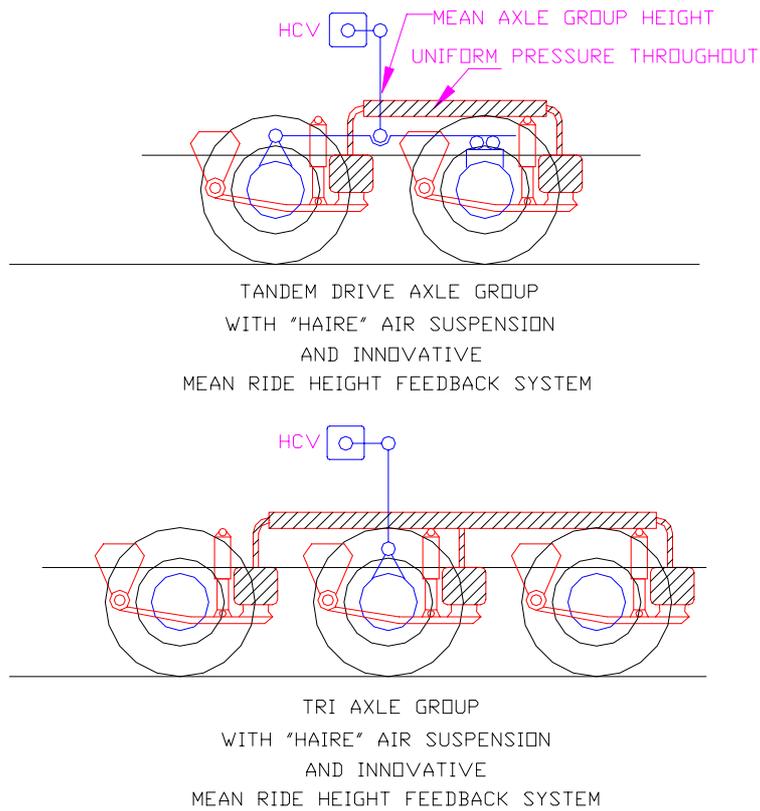


Figure 11. Details of the Haire fast response air suspension system.

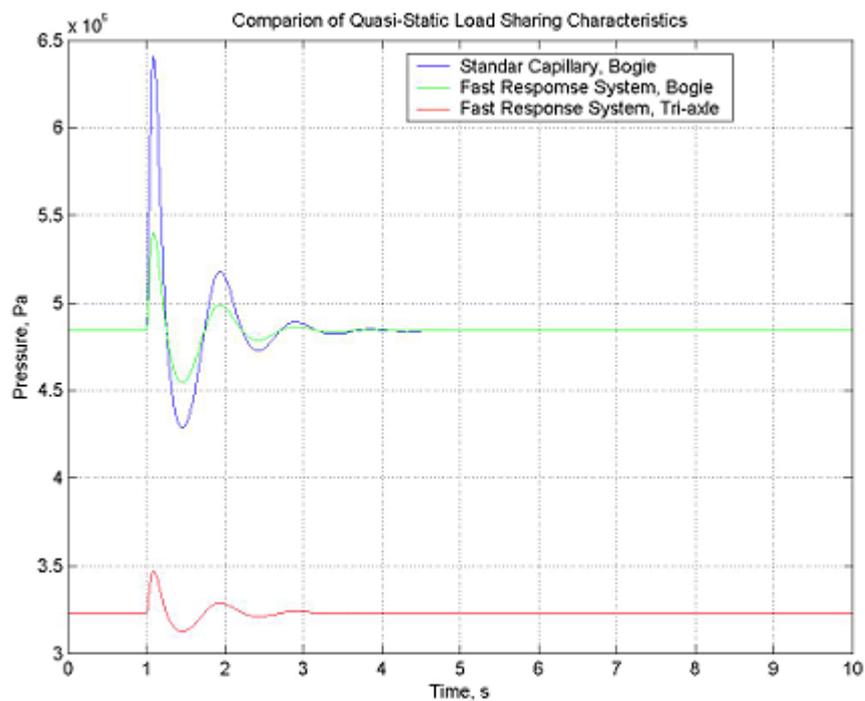


Figure 12. Airbag pressures in response to a step change in height for 3 suspensions.

The average increase in "road damage" arising from the first pressure spikes can be calculated from the increase on pressure and determined for a 4<sup>th</sup> power rule and a 12<sup>th</sup> power rule.

Table 3. Pressures and “road damage” for three suspensions.

Suspension	Average pressure (kPa)	Maximum pressure (kPa)	“Road damage” 1 <sup>st</sup> half cycle – 4 <sup>th</sup> power	“Road damage” 1 <sup>st</sup> half cycle – 12 <sup>th</sup> power
Standard capillary bogie	485	641	2.19	13.28
Fast response system bogie	485	540	1.32	2.43
Fast response system triaxle	323	347	1.21	1.80

The much greater potential road damage of the standard capillary tube suspension is readily apparent from the figures above.

And the more uniform pressure on the road is also apparent with the increase in pressure for the capillary tube suspension being 32.2% whereas for the two other suspensions the increases are 11.2% and 7.5%.

## RISK ASSESSMENT

Of concern with this new suspension was the vehicle response with operational and worn out shock absorbers, and the response to an airbag failure.

Tests of simulated airbag failures were undertaken at speed around a roundabout and at 100 km/h in straight ahead travel. These showed that the vehicle dropped uniformly onto the bump stops and that there was no unusual or difficult to control vehicle behaviour. This is because the loss of air on the “burst” airbag side is so rapid that, as the airbags on the other side cannot then support the load they collapse almost as rapidly.

Similarly the removal of shock absorbers created no problems. Around 10% of damping comes from the suspension bushes and the tyres, and 7% from internal damping. So the balance of the required 20% damping for road friendly air suspensions from the shock absorbers is only 3% so there is little effect on performance.

And this low requirement for damping from shock absorbers means that light single acting shock absorbers can be used for these suspensions.

## CONCLUSION

In spite of testing in the 1980’s and later showing that air suspensions are “road friendly” there is now serious doubts as to whether this is true in high speed situations (> 80 km/h). This is because current designs are not dynamically load sharing, and the design of height control systems is such that the suspension airbag pressures can vary significantly and help to generate chaotic behaviour in heavy trucks.

Theoretical considerations show that this is primarily due to the design of the HCV system including the small bore tube plumbing connecting the airbags.

An innovative modification to appropriate air suspensions results in these suspensions becoming dynamically load sharing. Theoretical modelling shows that the pressure rise in the airbags in the fast response system is about a third of that in the traditional system.

Though not done in this paper the same theoretical analysis can be used to demonstrate why twin HCV systems generate large differences in airbag pressures from side to side. These pressure variations are a significant cause of “problem vehicle” behaviour in heavy trucks and represents a safety hazard. Hence consideration should be given to reviewing the design of this style of suspension to avoid these deficiencies.

## REFERENCES

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