Characteristics of Fast Response Mean Ride Height Analogue Controlled Heavy Vehicle Air Spring Suspension System

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1. Introduction

Up to 1990 heavy vehicles utilized mechanical suspensions based on the use of multiple leaf springs connected to the vehicle's chassis rail using simple and reliable pins and bushes, hangers and pivoting arms. In these mechanical suspensions the lateral loads are transferred to the chassis via a combination of spring side bearing and hanger transmitted loads. Drive line generated axle torque resistance is provided by a combination of spring deflection in combination, on some suspensions, the use of a torque rod/s. Improved load sharing between axles is arranged by novel and varied use of rigid pivoted arms.

From 1990 onwards the use of bogie drive air bag suspensions increased significantly promoted by the opportunity for increased payload and more recently allowable increased gross combination mass. Air bag suspensions essentially utilize air bags or air springs (Hirtreiter 1965, SAE 1983) actively controlled to a set point ride height by a feedback back link connecting to one or more ride height control valves. On most air bag suspensions to date the feedback link is connected to the rear drive axle or axle cradle. The valves are connected to the chassis rails behind the rear axle and usually in very close proximity to the rear of the chassis rails. Typically most vehicles are fitted with twin ride height control valves to partially counteract vehicle corning loads and hence swaying / rolling. The air bags proper are connected in simple series or parallel / series from the control valve hitherto utilizing small diameter or capillary sized conduits. Typically ride height control valves are located at the rear of the chassis, for installation convenience, to minimize congestion and for adjustment and maintenance convenience.

Unfortunately heavy vehicle air spring suspension systems were introduced without full and proper understanding of their dynamic and in service characteristics This lack of understanding, compounded by improper engineering procedures typified by inadequate prototype in service road testing, resulted in systems entering service which possessed gross operation deficiencies (McLean 1999a). These gross deficiencies included installation of the ride height control valves to the chassis rails rearward of the rear drive axle and assuming both the vehicle chassis to be rigid and ideal load sharing between the drive axles. Improved dynamic analysis identifies these latter assumptions are grossly incorrect. Acting in combination these design deficiencies generate extremely adverse operating characteristics which greatly mar vehicle safety and operational characteristics. These same deficiencies significantly eroded operator and driver respect for and confidence in this relatively new heavy vehicle suspension technology. The operational problems, associated with existing air bag suspensions, has created a resurgence of the use of mechanical suspensions especially for vehicles hauling high centre of gravity (CoG) loads and or operating routes with back load potential.

The operational deficiencies of manufacturer supplied slow response air spring suspensions systems prompted efforts to minimize the same. The particular deficiency which prompted the development of the novel fast response systems was the inability of vehicles to operate on irregular surfaces subject to low traction typical of off road sand quarry operations without need for application of cross and differential lock and without partial tyre deflation. On highway operators where likewise experiencing unsatisfactory behaviour. This adverse operational behaviour included erratic steering and braking, evidence of poor load sharing and load transfer to the front axle, vastly increased levels of drive line vibration, reduced corning roll stability, vastly increased air compressor duty factor and significant scuffing of the front steer tyres to name just a few. These problems extended to loss of traction and poor loads sharing when moving slowly over irregular surfaces eg whilst moving into driveways and loading docks. In simple terms operators utilizing vehicles fitted with air spring suspensions, were experiencing varied problems and unusual vehicle behaviour hitherto unknown with mechanical suspended vehicles.

After approximately ten years of research and development it became evident to a local truck and bus repair operator that fast response air spring systems, incorporating a feedback system which monitored and controlled the mean axle ride height in the connected axle set, exhibited superior characteristics, relative to manufacturer supplied systems, over the complete ambit of heavy vehicle applications, operation speeds and conditions. These favourable characteristics heralded the local development of the novel air suspension system. In response to these characteristics an operator of a retrofitted vehicle approached the principle author to inform of the local development. From this initial unsolicited contact a strong and ongoing contact has been forged with the novel system inventor and manufacturer.

Commencing late 1998 the principle author was approached by a number of operators to examine the source for problems with essentially air suspended vehicles. This approach reactivated a long term significant interest and involvement in heavy vehicles complemented by significant background in engineering dynamic system modeling and significant knowledge of mechanics of solids, control and pneumatic systems. Based on inspection of numerous systems and based on initial analytical and simulation modeling of standard air bag systems major deficiencies vividly became evident. These initial concerns were subsequently confirmed and reinforced by more extensive modeling and simulation (Visman, 1999).

The initial theoretical investigations rapidly identified existing systems possessed fundamental design errors. These errors included:

- The monitoring and attempted control of the instantaneous ride height of the connected axle with a controller possessing adverse nonlinear and a response

slower than the variable being controlled (fundamental to modern control is the need for the controller to be faster than the system variable being controlled (Ogata 1979))
- Utilize (in most cases) twin ride height control valves located at or near the rear of the chassis and hence become exposed to erroneous chassis whip (McLean 2001a)
- Design of the feedback system based on the assumption the chassis was rigid
- Utilize small diameter conduits to promote capillary pneumatic damping
- Typically arranged the air springs in a crude series connection from the air valve/s and used cross lines of comparable diameter to that used to connect the bags onto each side
- Installed low damping rate mechanical dampers
- Installed feedback systems with seemingly haphazard details without any appreciation of the in service dynamic and non linear implications
- Installed the actual ride height control valves in seemingly haphazard orientations and arrangements without any appreciation of the in service dynamic and non linear implications.

In comparison the theoretical investigation suggested that a reliable state of the art system should exhibit the following:

- Monitor and control the mean ride height of the connected axle set:
- Utilize one ride height control valve
- Locate the ride height control valve at or near the chassis rear elastic curve node point
- Utilize fast acting plumbing between air springs.

It is not unexpected the inventor independently arrived at the above system design requirements but in addition identified the need to provide:
- Parallel extremely fast acting connection between bags along each side with an essentially valve isolated cross line of vastly different diameter
- Utilised inherent and biased orifice pneumatic damping.

System Comparison : Hardware

As a result of the independent developments two distinctly different categories of air bag suspension systems existed late 1998; notably existing manufacturer systems and the novel system. A summary of the hardware comparison between existing manufacturer systems to that used in the novel system is presented in Table 1 following. An examination of Table 1 indicates that the majority of existing air bag suspension systems utilize two ride height control valves located at or near the rear of the chassis with the feedback link connected to the rear axle or axle cradle. Furthermore the conduits between air bags are typically small diameter capillary lines. As a result existing systems exhibit slow response. A further significant error with the set up of existing air bag systems is the attempt, via the use of two ride height control valves to control cornering roll (McLean 1999b). Unfortunately this attempted control action is deficient due to the excessively slow system response. Furthermore attempt to control the cornering roll induced ride height deviation during actual highway speed cornering operations is dangerous due to valve stiction, dead band, system response delay time, the system slow response and possibility of back flow. A further complication is the flow to the bags experiencing load increase (ie those on the outside of corner) is subject to a low magnitude pressure differential whereas the flow from the bags experiencing load decrease (ie those on the inside of corner side) is subject to a large pressure differential. The latter results in rapid venting to atmosphere. These latter characteristics confirm that existing air bag systems and their associated control systems exhibit strongly non linear behaviour (Mclean 2001b).

Table 1 Hardware comparison between existing and novel air bag suspension systems

Component	**Existing slow response** [1]	**Novel** [2]
System response	slow	fast
System natural frequency	low (~2.7 Hz)	High (> 20 Hz)
conduits	Capillary lines	Large diameter with localized biased orifice components
Number of valves	2 typical	1
Location of valve	At or near rear of chassis	Near rear chassis node point
Feedback connection	From axle or axle cradle extension	From ride height floating beam
Air spring connection	series	parallel
Connection arrangement	variable	fixed
Damping	Capillary	Orifice
Maximum damping effect	Low frequency	High frequency
Additional mechanical dampers	High dependence	Low dependence
Feedback linkage	Seemingly haphazard	Direct
Cross line	Seemingly haphazard	Small diameter checked through valve
Valve location and orientation	Seemingly haphazard	Strategically located

[1] – based on inspection of over 20 heavy vehicles
[2] – based on inspection of 2 heavy vehicles and manufacturer details

System Comparison : Operation Characteristics

The difference in hardware between existing and state of the art systems generates significant differences in direct in service system behaviour and characteristics. These difference are summarized in Table 2 following. An examination of this Table indicates the novel state of the art system exhibits vastly superior service characteristics than that exhibited by typical existing systems.

Table 2 Comparison between existing and novel system in service behaviour

Characteristic	**Existing slow response [1]**	**Novel [2]**
Load sharing	Poor	Optimal
Pressure differential between bags	Large	Minor
Pressure modality	Modal of order [3]	Single modal
Deviation in axle / ride height	Large	Minor – mean variation only
Torque rise	Significant	Negligible
Drive line vibrations	Significant	Negligible
Cabin / seat transverse vibrations	Significant	Negligible
Bump steer	Significant	Negligible
Sensitivity to erroneous chassis rear end flex	Significant	Minimal
Cornering roll	Significant	Minimal
In service dynamic loads	Large	Minimal
Braking performance	Poor	Optimal
Braking Consistency	Poor	Consistent
Ability to rapidly response to changing road conditions	Poor	Excellent
Risk of deviated bag pressure at corner set up	High	Low but finite

[1] – based on inspection and passenger test drive in over 10 heavy vehicles
[2] - based on inspection and passenger test drive in 2 heavy vehicles
[3] – based on analysis of actual test data

System Comparison : 'Flow On' Characteristics

The differences in operation characteristics associate with distinct differences in secondary or 'flow on' characteristics. A summary of these flow on differences are summarized in Table 3 following. An examination of Table 3 confirms the novel state of the art systems attracts paramount 'flow on' benefits. It is expected these secondary benefits will attract long term benefits to vehicle operators, the road transport industry in general and greatly enhance road safety.

The findings of this work are consistent with the findings of the Cambridge University Transport Research Group (http://rage.eng.cam.ac.uk/trg/) insofar as in motion pavement monitoring of vehicle dynamic axle loads has identified that heavy vehicles fitted with 'road friendly suspensions' exhibit higher dynamic tyre forces than conventional mechanical suspensions. Furthermore the magnitude of the in service tyre forces generated by existing air spring suspension systems is extremely dependent on the system mechanical damper state of repair.

Table 3 Comparison of 'flow on' characteristics between existing and novel systems

Characteristic	Existing slow response [1]	Novel [2]
Drive line component failure	Frequent	Minimal
Seat transverse vibrations	Significant	Minimal
Vibration frequency characteristics	Subharmonic	High
Steering wheel vibrations	Significant	Minimal
Load sharing	Poor	Optimal
Braking	Erratic	Optimal, consistent, reliable
Air consumption	High	Minimal
Steer tyre response	Scuffing to outside edges, extreme scalloping	Uniform wear
Typical steer tyre life	40,000	120,000 +
Drive axle cross lock / differential lock application	Frequent	Minimal
Suitability for off road application	Poor	Excellent
Tolerance to pavement corrugation	Poor	Excellent
Damage to roads	Significant	Minimal
Damage to vehicle and loads	Significant	Minimal
Sensitivity to maintenance	Significant	Minor
Sensitivity to system deviations and state of repair	Significant	Minor
Stability during cornering	Poor	Excellent
Performance without mechanical dampers [3]	Extremely adverse	Excellent – inherent damping
Road train response [3]	Rear trailer snaking +/- 1m	Minimal snaking – out of sight out of mind
Risk of driver fatigue [4]	High	Minimal

[1] – based on inspection and passenger test drive in over 10 heavy vehicles
[2] - based on inspection and passenger test drive in 2 heavy vehicles
[3] – based on third party reports from actual in service vehicles
[4] – implied association.

System Comparison : Independent Evaluations and In Service Findings

The successful and confident application of the novel state of the art air bag suspension system is reinforced by extensive testing and evaluation conducted on the system to date as detailed in Table 4. The findings of this testing and evaluation is consistent with the successful ongoing operation on over 50 retrofitted vehicle systems a number of which include major road train applications. The system improvement effected by retrofitting standard systems in all cases exceeded operator expectations.

Table 4 Test work / Analysis Conducted

Testwork	State of the art
Risk Analysis	Full risk assessment
In service testing	Extensive road testing
Emergency Situation	Cornering subject to burst air bag condition
In service systems	Close monitoring and ongoing operator feedback

Novel system: Complete Evaluation

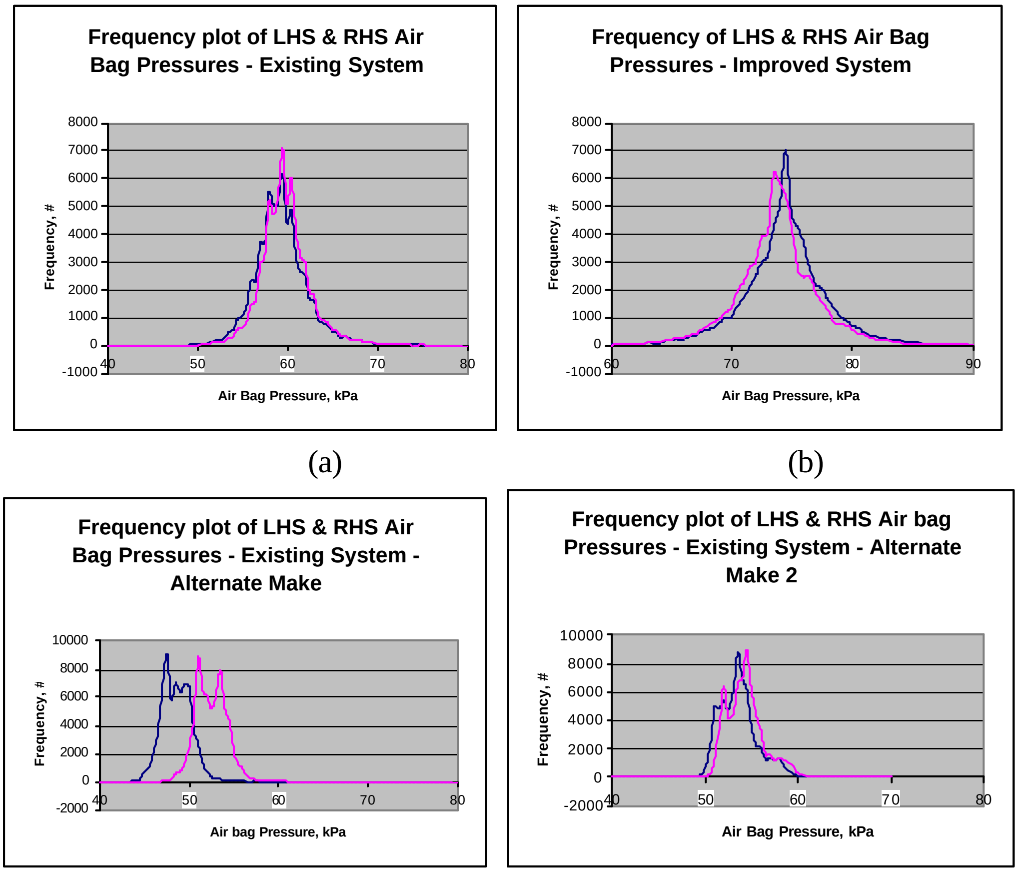
For engineering completeness it is appropriate to list possible negatives associated with the novel system. These negatives include:

- the large diameter manifolds add to the in rail web and along chassis conduit congestion, the plumbing demands large diameter connection to and through the air bags seat and attachment brackets proper,
- relatively large diameter conduits may need to pass through the chassis rail webs,
- installation frequently requires reversal of the rear of chassis cross members,
- the routing of the large diameter manifolds typically underneath the cross member/s exposes the tube surface to scuffing wear (the extent of which is readily evident),
- the system, for optimal reliability, is installed with high pressure hydraulic fittings (so attracting higher installation cost),
- the system utilizes a slightly more extensive feedback system, and,
- the single ride height control valve is invariable more difficult to access.

An examination of the foregoing system negatives suggest the same are far outweighed by the system positives (refer tables 2 to 4). A number of the above negatives are also directly counter opposed by system positives. Notably the ride height control valves can be positioned to slightly and strategically bias one axle (usually the rear) and to bias (usually the left) one side of the vehicle to adjust for general road camber. This location void of ready rear of chassis access reduces the opportunity for drivers to effect ad hoc system ride height, hence drive line angle, adjustments. Further the use of a single valve ensures the complete system responds to a common valve control and state of repair. A further system positive is the ride height walking beam and feedback system is inherently simple, robust and reliable.

System Comparison : Air Bag Pressure Characteristics

The adverse behavior of typical existing systems is verified by statistical analysis of the air spring pressures observed on operating vehicles. Typical histograms of air bag pressures for different suspension are depicted in Figure 1. An examination of Figure 1 indicates the improved air suspension system exhibit the least statistical distribution standard deviation and the low magnitude difference between the left and right hand sides. Here it should be noted Figures 1(a) and 1(d) depict pressures traces for both the LHS and RHS air spring on vehicles utilizing one ride height control valve and hardware small diameter cross connection.



(a) (b) (c) (d)

Figure 1 Comparison of Air Bag Frequency Histograms – (a) Existing System (b) Improved System, (c) Existing System - Alternative Make, (d) Existing System - Alternative Make 2

System Comparison : Seat Pad Vibration Characteristics

One paramount driver environ and well being characteristic is the magnitude and spectra of the seat pad vibrations. In view of this significance the vertical vibration characteristics of three different heavy vehicles are compared. This comparison is summarized in Figure 2. An examination of Figure 2 indicates the state of the art system (series 3) exhibits vastly reduced weighted average seat pad vibrations relative to that exhibited on 'two' other heavy vehicles utilizing different air bag suspension systems (Series 1 and Series 2). The unusual feature of the test results depicted in Figure 2 is that Series 2 and 3 correspond to test data collected from a single heavy vehicle (tipper rigid configuration) installed, for test purposes, with a inter changeable air suspension system. Notably the system was interchanged from the original as supplied system to the novel system. Series 2 corresponds to the original suspension tested with the vehicle traversing off road at 15 km/h, whereas, Series 3 corresponds to the same vehicle fitted with the novel suspension traversing the same off road route at 40 km/h. In comparison Series 1 represents the average test duration seat pad vibration characteristics of prime mover F3 tested and reported in the FORS investigation into heavy vehicle dynamics and consequent effects (http://www.dotrs.gov.au/land/ truckrpt.htm).

The extent of vibration reduction implied by the weighted vibration spectra characteristics in Figure 2 is emphasized by evaluating average weighted vertical acceleration (a_w). The evaluated average weighted acceleration for the spectra presented in Figure 2 are presented in Table 1 following.

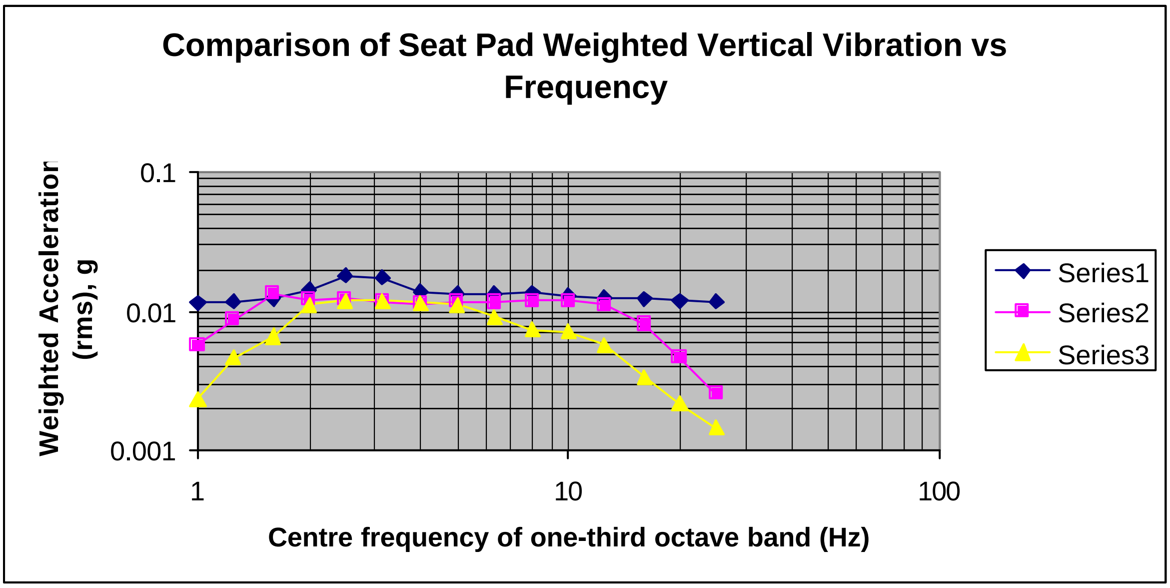


Figure 2 Comparison of seat pad weighted vertical vibration versus frequency

Table 5 Average weighted vertical acceleration (a_w)

	Series 1	Series 2	Series 3
Test Conditions	300 km highway	15 km/h Offroad	40 km/h Offroad
As reported	0.053	0.040	0.031
Relative as reported	1.68	1.29	1
Relative adjusted to 40 km/h		2.54	1

System Comparison : Inherent Pneumatic Damping Characteristics

By use of the analysis presented by Andersen (1967) it is possible to effect comparison of the damping characteristics of existing systems (capillary controlled) and the novel system (orifice controlled) versus in service frequency. This theoretical comparison is summarized in Figure 3. An examination of this Figure indicates the larger magnitude inherent damping characteristics of orifice controlled damping (Series 1) relative to capillary controlled damping (Series 2) at typical in service frequencies (typically 8 Hz for highway operation). The low magnitude of capillary controlled damping at the higher frequencies implies vehicles fitted with capillary lines must rely on mechanical shock absorbers in high state of repair for effective highway speed in service damping. In comparison, at highway speed, the novel orifice based system possesses inherent stable damping independent of the state of repair of any mechanical shock absorbers fitted. The same associates with both direct and indirect safety benefits and implies, most significantly, genuine road friendly status at typical highway speed.

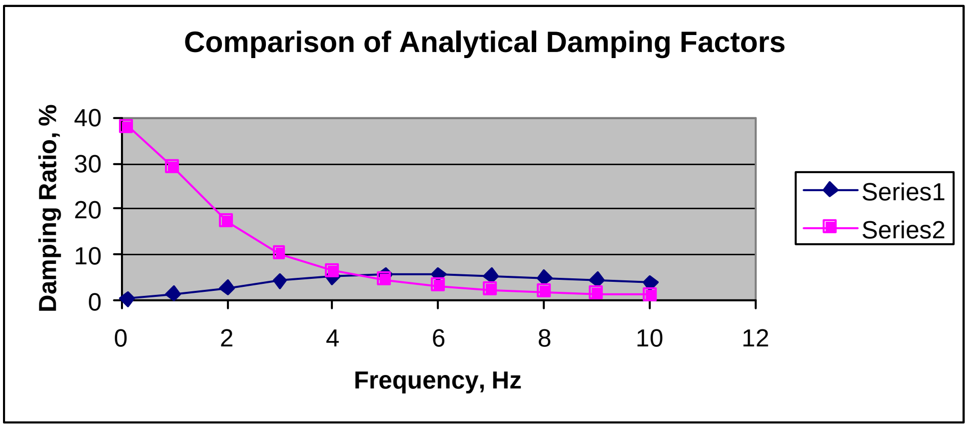


Figure 3 Comparison of predicted orifice controlled damping (Series 1) and capillary controlled damping (Series 2)

Road Testing

Due to system complexity full knowledge of existing air bag suspensions dynamic behaviour is only possible by rigorous extensive road testing under actual in service conditions at highway speed. This road testing should be complemented by in motion in pavement monitoring of wheel loads and bridge response to various vehicle suspension systems (including mechanical). Such testwork should be conducted for the complete ambit of operation conditions including load CoG, GVM, fuel stowage, cabin and sleeper tare, GCM, chassis flexibility, componentry rotational balance, road speeds, pavement camber and pavement roughness.

Conclusion

The foregoing comparison reveals the novel fast response mean ride height analogue controlled system attracts considerable advantages. So much so that this novel system heralds a new benchmark for heavy vehicle genuine road, vehicle and driver friendly bogie suspensions. The same is also confirmed by successful retrofitting, of this novel state of the art system, to over 50 vehicles conducting varied applications in the national road transport industry. The most notable improvements include vastly improved driver environs, vehicle road interaction, vehicle safety and general road safety. These major improvements imply, in the long term, the system will rank equally with other Australian world leading technology developments to the full credit of the inventor and manufacturer. This local major development will strengthen the national road transport industry's ongoing standing as the world benchmark. This world benchmark status will be reinforced by the system's significant contribution toward the attainment of a zero road toll.

References

Andersen, B. W., (1967), The Analysis and Design of Pneumatic Systems, John Wiley & Sons, New York.
Cambridge University Transport Research Group, http://rage.eng.cam.ac.uk/trg/
Federal Office of Road Safety (FORS) (2000), Investigation into the Specification of Heavy Trucks and Consequent Effects on Truck Dynamics and Drivers: Final Report, http://www.dotrs.gov.au/land/truckrpt.htm.
Hirtreiter, A. B., (1965), Air Springs, Machine Design, April, pp 104 – 112.
McLean, A. G., (1999a), Prime Mover Air Suspension Ride Height Control Malfunction, Proceedings Technical Program of the International Pacific Conference on Automotive Engineering (IPC-10), Melbourne, Australia, pp 281 – 285.
McLean, A. G., (1999b), Active Computer Controlled Air Suspension Systems for Heavy Prime Movers – A Conceptual Evaluation, Proceedings, Intelligent Transport Systems Australia – Smart Solutions at Work – 4th International Conference, Adelaide, South Australia, May 1999, CD ROM, Conference Abstracts p 44.
McLean, A.G., (2001a), Rear End Chassis Flex – Erroneous Feedback to Heavy Vehicle Air Bag Suspension Ride Height Control Systems, Proceedings MSMS 2001 Conference, University of Wollongong, Wollongong, February, 2001, pp 229 – 234.
McLean, A. G., (2001b), Non Linear Vibration Phenomena of Prime Movers, Proceedings MSMS 2001 Conference, University of Wollongong, Wollongong, February 2001, pp 217 – 221.
Ogata, K., (1979), Modern Control Engineering, Prentice Hall.
SAE Handbook, (1983), Vol 4, SAE Information Report J511a Pneumatic Spring Terminology (Section 77.08).

Visman, R.,(1999), Dynamic Characteristics of Heavy Prime Movers – Kenworth Air Glide 100 Bogie Suspension, BE Thesis, Faculty of Engineering, University of Wollongong.