Improving Road Safety by Improving Air Suspended Heavy Vehicle Highway Speed Load Sharing Characteristics

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Biography

Mr. Bohao Li graduated from Shanghai University of Engineering Science in 2001 with a Bachelor Degree in Automotive Engineering. He was awarded the Degree of Master of Engineering Practice in 2002 from the University of Wollongong and currently is a postgraduate research student. Mr. Bohao Li has been involved in heavy vehicle air suspension research since he began postgraduate studies at the University of Wollongong and further research work is in progress.

Abstract

This paper presents the findings from simulation studies of the behaviour of both capillary and orifice controlled heavy vehicle air suspensions. In this simulation the behaviour of bogie and tri axle groups subject to a bump at highway speed is examined. Some particular air-suspended heavy vehicle dynamic roll characteristics are then briefly discussed. This paper reveals that current air suspension designs with capillary transmission lines are not only "road unfriendly" but also dangerous if their dynamic behaviour is considered. Furthermore existing truck trajectory computer simulation packages cannot predict the characteristics of air-suspended heavy vehicles so generating totally wrong simulation results.

1. INTRODUCTION

One of the major problems that current air suspension designs exhibit is the insufficient airflow through the capillary transmission lines between the leading and trailing axles [1][3]. If the excitation signal is in the low frequency band, it takes much longer for the capillary transmission lines to respond, due to the excessive damping, compared with large diameter orifice transmission lines. If the excitation signal is in the high frequency band, capillary transmission lines will simply effectively block hence minimal airflow flows through the transmission lines. Therefore, if capillary transmission lines are used, it fails to achieve ideal load sharing between the leading and trailing axles hence high dynamic load coefficient (DLC) result. Excessive dynamic load is adverse to road safety as well as road friendliness. Furthermore the chassis and suspension components are continuously subject to large forces. If the suspension positioning components break, vehicle loss of control is inevitable. Large vertical dynamic load can also increase the possibility of losing contact between the wheels and the ground, generating potential handling problems. This adverse wheel pavement contact or poor load sharing can significantly effect braking performance, in some cases, causing ABS (where fitted) brake system malfunction.

Most current air suspension designs, which use such capillary transmission lines, are not “road friendly” subject to actual dynamic situations. Notably current criteria adopted in Vehicle Standards Bulletin (VSB) 11 to certify so called road friendly suspensions specifies only “static load sharing to within 5 per cent”. Hence this criteria cannot effectively determine the actual at operating speed road friendliness characteristics of a particular suspension system. Similarly, most current heavy vehicle simulation packages cannot predict the handling and braking characteristics of air-suspended heavy vehicle as such packages typically assume ideal load sharing between all axles and invariant spring stiffness characteristics. These deficiencies demand actual vehicle dynamic testing at highway speed.

2. CHARACTERISTICS OF THE CAPILLARY AND THE LARGE DIAMETER ORIFICE TRANSMISSION LINES

A simplified model of a transmission line system is shown as follows:

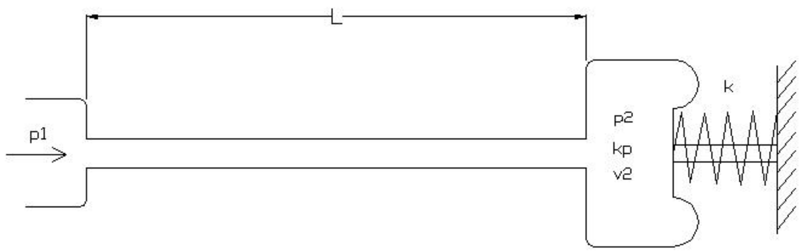

Figure 1: Simplified transmission line physical model [6]

Where:

p_1 – Supply pressure change, Pa
p_2 – Airbag pressure change, Pa
k_p – Air spring stiffness, N/m
v_2 – Airbag volume change, m^3
L – Length of the transmission line, m
k – Tyre stiffness, N/m

The transient pressure responses for a 4.15 mm diameter capillary and a 50.8 mm diameter orifice transmission lines subject to a unit step input are illustrated in Figure 2. This simulation is based on Anderson’s transient analysis for pneumatic systems [6] and generated by MATLAB.

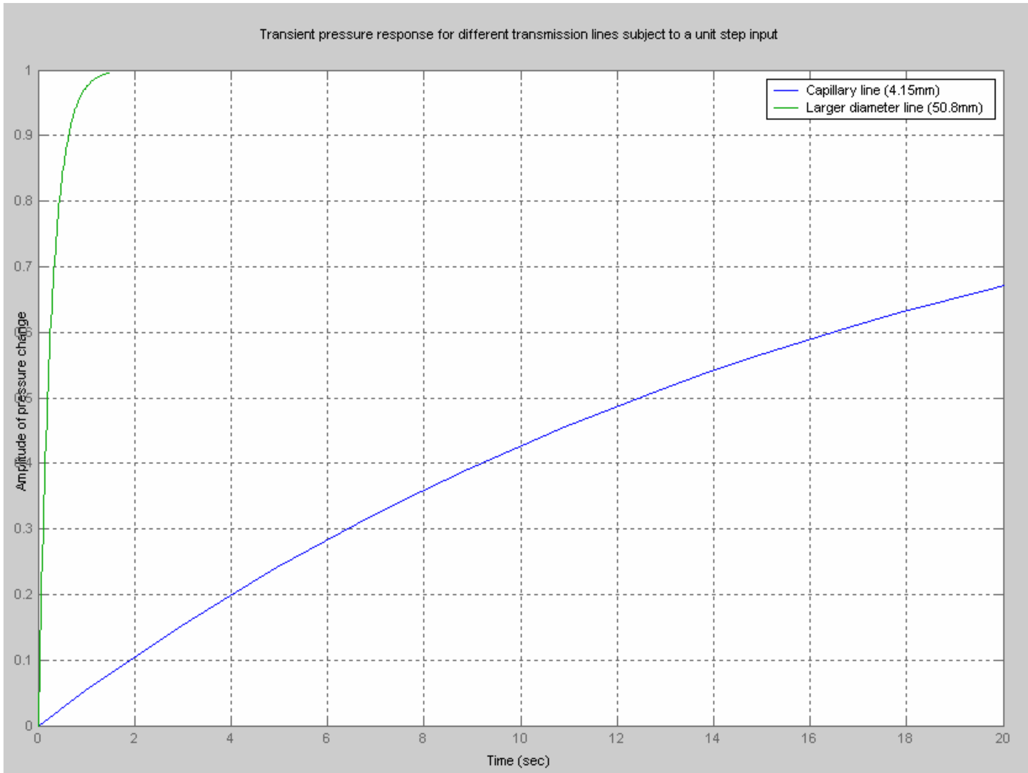

Figure 2: Transient pressure response for different transmission lines subject to a unit step input

An examination of Figure 2 indicates that the capillary transmission line exhibits significant response delay. Considering the same time duration, for example, at 2 seconds, since the pressure change of capillary is far less than that of the orifice transmission line, significantly more air is compressed in the leading airbag rather than transferring through the transmission line to the trailing air spring or airbag.

The frequency responses of these two systems are shown in Figure 3. This Figure reveals that the large diameter transmission line exhibits better performance over a much wider frequency band compared with that exhibited by the capillary transmission line system.

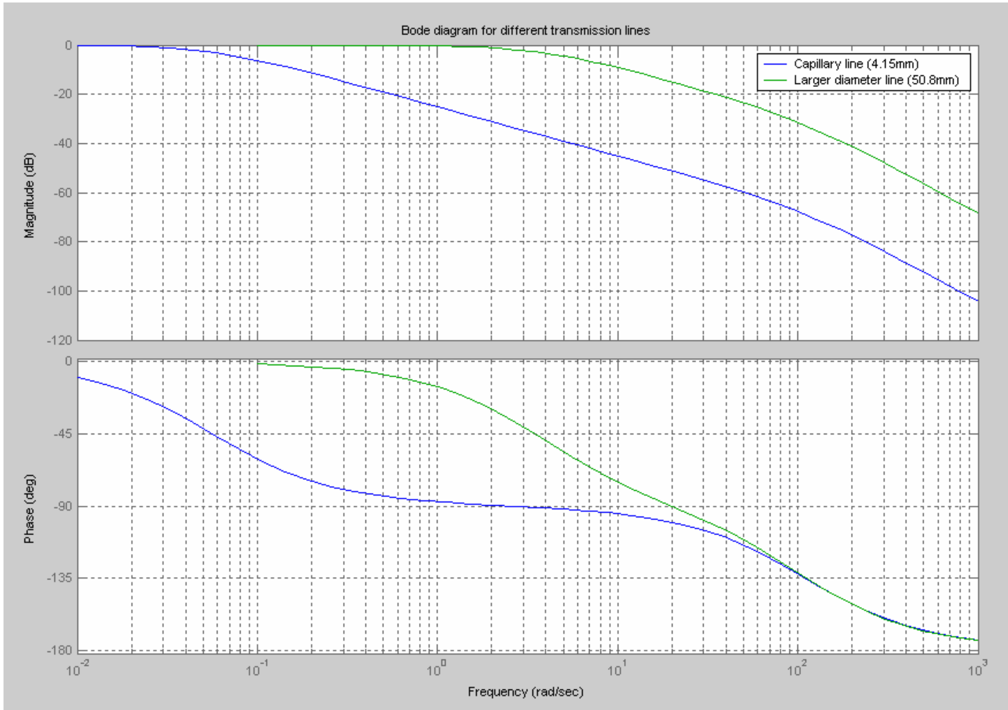

Figure 3: Frequency response for different transmission lines

3. CRITICAL PISTON STROKE VELOCITY TO ACHIEVE MAXIMUM AIRFLOW

For any pneumatic transmission line the maximum airflow or critical mass flow that can pass through it will occur and only occur when the velocity of the airflow equals the local sound speed and that the pressure differential across it is 50% of the supply pressure. Here, the critical airbag piston stroke velocity that generates the critical mass flow is determined for improved understanding of the severe limitations of existing capillary controlled suspension systems.

The critical mass flow is determined by:

$$W_{cr} = \frac{A_{12} P_1}{\sqrt{T_1}} [\frac{\gamma g}{R} (\frac{2}{\gamma + 1})^{(\gamma+1)/(\gamma-1)}]^{\frac{1}{2}} \qquad (1)$$

where:

W_{cr} – Critical mass flow, kg/s;

A_{12} – Section area of the transmission line, 1.34e-5 m^2 for the 4.15 mm diameter capillary; 3.14e-4 m^2 for a 20 mm diameter orifice inlet in the 50.8 mm diameter transmission line;

P_1 – Airbag pressure, 125568 Pa for 3200 kg vertical load applied on a 10'' (254 mm) diameter airbag for both cases;

T_1 – Operation temperature, 303 K assumed;

γ – Ratio of specific heats, γ = 1.4;

g – Gravitational acceleration, 9.81 m/s^2;

R – Gas constant, 287.07 N-m/kg-K.

The relationship between mass flow and volume flow is:

$$W_{cr} = q_{12} \times \rho_{av} \tag{2}$$

where:

q_{12} – Volume flow rate, m^3/s.

ρ_{av} – Average air density in the airbag, 1.44 kg/m^3 under 3200 kg vertical load on a 10'' diameter airbag;

For a small displacement of an air spring, it follows that

$$V = \frac{dx}{dt} = \frac{q_{12}}{A_p} \tag{3}$$

where:

V – The critical airbag piston velocity, m/s;

x – the vertical displacement of the piston, m;

t – time, s;

A_p – The effective area of the 10'' diameter airbag, 0.051 m^2.

Substituting the appropriate parameters the critical velocity for a 4.15 mm diameter capillary to be approximately 0.17 m/s while the corresponding value for the 50.8 mm diameter orifice line (with 20 mm diameter inlet or orifice) is approximately 3.9 m/s. Obviously, the larger diameter transmission line not only exhibits more airflow but also better performance under higher vehicle speed as a vertical airbag movement of 0.17m/s associates with low speed operation.

4. DYNAMIC LOAD SHARING SIMULATION FOR DIFFERENT TRANSMISSION LINES AND WHEEL GROUPS

It is suggested to use tri-axle groups on prime movers to decrease in service DLCs , improve payload capacity and simplify loading [4]. This heavy vehicle improvement can be effected by adding a liftable non-drive axle with 19.5'' dual tyres forward of the standard bogie drive group as depicted in Figure 4.

Figure 4: A B-double fitted with tri-axle group and the 50.8 mm diameter orifice transmission line

(Photo courtesy: the Haire Truck & Bus Repairs Pty Ltd)

To evaluate this postulation a SIMULINK model was established to simulate three different prime movers situations namely: (a) bogie axle group with capillary transmission lines; (b) bogie axle group with large diameter orifice transmission lines; and (c) tri-axle group with large diameter orifice transmission lines. Further model details, summarized in Figure 5, are presented in [4].

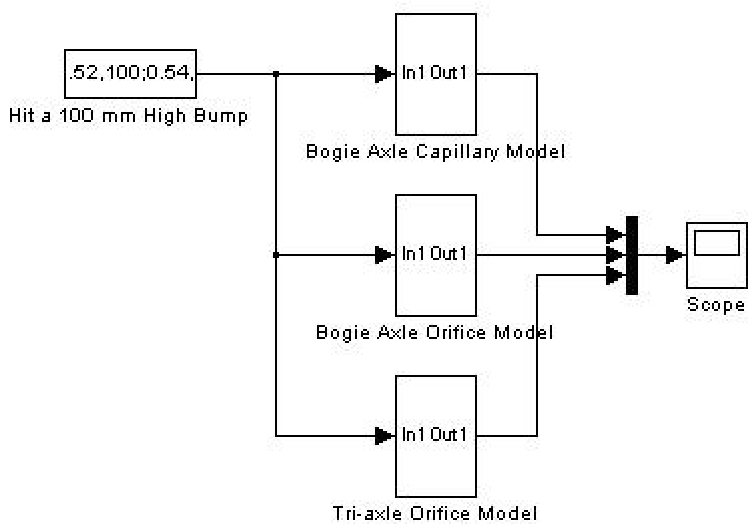

Figure 5: The SIMULINK model of three prime movers with different transmission lines and wheel groups

The input signal is assumed to be a 100 mm high bump hit at the speed of 100 km/h. The excitation time lasts 0.04 s, which is slightly shorter than the delay time between leading and trailing axles at 100 km/h, which is 0.0432 s. The transient pressure response for these three models is shown in Figure 6:

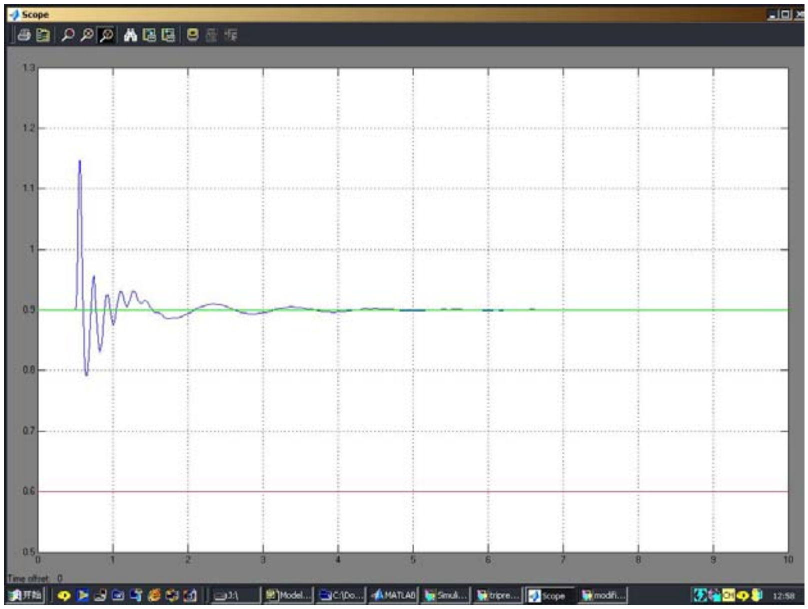

Figure 6: Transient pressure response of three prime movers with different transmission lines and wheel groups

An examination of Figure 6 reveals that the pressure in the two orifice transmission line cases is uniform. Furthermore because the tri-axle group has inherently lower pressure (assuming constant axle set load), this system exhibits optimal load sharing. This benefit is summarized in Table 1 below:

Table 1: Dynamic load coefficient (DLC) of three different air suspension models

Type	ΔP_{max} (MPa)	P_{ave} under 18t load (MPa)	DLC_{max}	$\Delta P_{max}/P_{ave}$
Bogie Capillary	0.25	0.9	1.28	28%
Bogie Orifice	0.00045	0.9	1.0005	0.05%
Tri-axle Orifice	0.00015	0.6	1.00025	0.025%

5. LOAD SHARING EFFECT ON BRAKE PERFORMANCE

The benefit of improved load sharing is evident by noting an aged semi trailer combination, with an odometer reading exceeding 1.5M km, fitted with a biased flow orifice controlled large diameter transmission line mean ride height controlled bogie drive and triaxle air suspensions consistently outbrakes comparable ‘off the production line’ units especially those fitted with ABS braking systems. The ‘aged unit’ typical exhibits measured braking performance exceeding 92% on all axles. This same unit exhibits tyre change overs at 225,000 km and minimal drive line, cabin and driver seat vibration levels. This same vehicle recently successfully, at highway speed, steered out of a critical unexpected dangerous situation necessitating a major trajectory deviation. This deviation according to other experienced drivers would have otherwise precipitated a major heavy vehicle rollover if attempted in any other air suspended heavy vehicle.

6. SUMMARY OF DYNAMIC ROLL CHARACTERISTICS

The roll characteristics of a quasi-static suspended vehicle model have long been understood. However, in the reality, a vehicle is always a dynamic system. Aleksander Hac [7] predicted a second order roll model which is depicted as:

$$I_s \frac{d^2\phi}{dt^2} + C_\phi \frac{d\phi}{dt} + \kappa_\phi \phi = T_\phi = M_s a_y (h - h_r) \qquad (4)$$

where:

I_s – The moment of inertia of vehicle body about roll axle, kg-m²

C_φ - Suspension roll capacity, N-m-s/degree

κ_φ - Suspension roll stiffness, N-m/degree

T_φ - Moment of external loads about the roll axis, N-m

It should be noted that for an air suspended vehicle, the suspension roll stiffness κ_φ, similar to the vertical stiffness, is non-linear. However, for convenience, it is treated as a constant for relatively small roll angles. For most vehicles, the above second order roll model is an under-damped model hence response overshoot is expected. This implies it is possible for a vehicle to exhibit excess body roll when effecting turns at speeds well within the lateral acceleration threshold limit. The excessive body roll will increase the outside airbag pressure significantly and it is not uncommon that the airbag pressure will exceed the supply pressure of the reservoir. At that instance, the outside airbag is compressed and the height control valve is incorrectly actuated attempting to correct the ride height. (This is especially paramount when dual ride height control valves are used.) The result will be devastating. The outside airbag will collapse further due to the backflow. Even for those vehicles equipped with backflow check valves, the situation is only marginally improved. This is because the check valve will discharge to the atmosphere if the airbag pressure exceeds the supply pressure. However, due to the large pressure difference between the airbag and the atmosphere, the discharging process is much faster than the charging process, which will cause the outside airbag to collapse further.

The foregoing scenarios highlights that it is paramount to conduct dynamic roll testing at actual highway speed to complement static tilt table testing. Such dynamic testing will reveal the paramount actual heavy vehicle roll characteristics.

7. HEAVY VEHICLE TRAJECTORY SIMULATION PACKAGE DEFICIENCIES

Current commercial heavy vehicle trajectory simulation packages, such as “TruckSim”, are totally deficient in simulating air-suspended vehicles because they generally have three significant defects. Firstly, they assume the heavy vehicle is quasi mechanical sprung, secondly all suspensions are assumed to exhibit ideal road sharing which only occurs when static even for air suspended axles. Thirdly, invariant suspension vertical spring stiffness is assumed. However, for any air-suspended vehicles, the spring stiffness is not a constant due to the inherently non-linear behaviour of the air springs. Due to these significant deficiencies these simulations will be of no practical value for predicting existing air suspended heavy vehicle behaviour with the simulation exercise simply corresponding to the well known adage “garbage in garbage out”, and at worst, totally wrong simulation predictions result. Noting the existing deficiencies it is paramount current heavy vehicle simulation package be significantly improved. In particular valid simulations are only possible for heavy vehicles fitted with rapid response transmission line systems fitted to all air suspended axles. This confidence is consistent with such vehicles behaving like mechanical sprung vehicles hence they accurately satisfy the simulation package paramount assumptions so accurate vehicle trajectory and behaviour predictions result.

8. SUMMARY OF ADVERSE LOAD SHARING CHARACTERISTICS

A summary of the adverse implications of adverse dynamic or in service load sharing, in particular regard heavy vehicle road safety, is presented in Table 2 presented as Appendix 1.

9. CONCLUSION

This modeling and simulation reveals fast response air suspension system load shares very efficiently and exhibits rapid response under dynamic situations. Notably the pressure response is far smoother than existing standard air suspensions and the dynamic load coefficient (DLC) is lower. Improved load sharing not only assists road friendliness but also enhances road safety by , in turn, improving both handling and braking performance. The significantly lower DLC will assist to protect both the highway pavement and the vehicle by reducing the risk of prevent premature component failure. The ride quality is also improved so reducing driver fatigue, which is a significant contributing factor in many heavy vehicle accidents.

Commercial heavy truck trajectory simulation packages must be improved to incorporate time and spatially varying dynamic load sharing parameters and non-linear spring stiffness parameters. Without these important parameters, inaccurate dynamic performance prediction of existing standard air-suspended heavy vehicles will continue. Furthermore roll over and road friendliness specifications should be enhanced to include dynamic testing at highway speed.

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Keywords

Heavy vehicle safety, air suspension, capillary transmission line, dynamic load sharing, dynamic roll characteristics

Appendix 1 Safety Implications of Existing Adverse Dynamic Load Sharing

Feature	Problem	Result
Brake adjustment	Inconsistent dominant axle braking	Operators / drivers back off both lead and trailing axle off and rely solely on the steer axle
Brake Operation	Braking occurs on a dominant axle with the other axle skidding	Uncontrolled braking, marginal vehicle stability and generation of tyre flat spots. Proof – a dated 1.5M km + HV with optimal load sharing consistently outbrakes new HVs especially those fitted with ABS. Also this same vehicle successfully steered out of a critical road situation avoiding a serious road accident – other HVs simply would have crashed in the same situation.
ABS Brake Failure	Poor dynamic load sharing	Erroneous signal to ABS control hence complete failure of ABS systems
Steering	Sudden change of road condition	Extreme and sudden marginal stability
Steering	Alternate dominant rear axle	Vehicle continually changes from SWB to LWB generating erratic / unpredictable steering
Steering	Inconsistent and unpredictable air pressures eg pressure can be low, normal or high entering curve or along straight	Gross instability can occur with extreme risk of roll over Vehicle wanders due to drive steer effect
Steering	Entering succeeding opposite lock curve – air spring pressures grossly inconsistent	Gross vehicle instability and associated high extreme of vehicle loss of control
Steering	Vehicle with twin ride height control exiting long sweeping curve	Air springs on outside of turn overpressurize generating chaotic lever effect hoisting chassis rail catapulting vehicle across lane
Stability	Twin height ride control	On entering corner with high CoG back flow from air springs may occur resulting in sudden gross vehicle instability and extreme risk of vehicle rollover
Tyre wear	Tyre scalloping / irregular wear pattern	Reduced braking performance and stability / higher vibration level induced to driver causing higher risk of driver fatigue
Driver Performance	Invariant extreme vigilance	High risk of rapid onset of driver fatigue, high risk of loss of control in critical conditions, high risk of physiological damage and body stress / discomfort
Traction	Marginal tractions situations e.g. water, mud, snow, spillages and stock exertions	High risk of sudden complete traction loss and vehicle control Need for sudden application of diff and cross

		locks Intense driver vigilance demanded
Traction	Strongly irregular surfaces	Wheel spin, loss of traction and tyre damage, engine mismanagement, ABS control failure. Need to apply diff and cross locks to proceed.
Heavy Vehicle Trajectory Computer Simulation	Phenomena strongly non linear, time and camber dependent and in some cases chaotic responses. Significant improvements in modeling details and software enhancements necessary.	Simulations result in stable predictions which significantly deviate from actual trajectories and stable. In most cases simulations effected assuming vehicle is mechanical sprung with flat tyres void of actual operation speed calibration. Simulations consistent with the adage “rubbish in rubbish out”