Dynamic Load-Sharing of Longitudinal-Connected Air Suspensions of a Tri-Axle Semi-Trailer

School of Transportation Engineering, Hefei University of Technology
193 Tunxi Rd, Hefei 230009, China
Tel: 86-551-2919160
Mobile: 86-13665608364
Fax: 86-551-2901960
E-mail: leochen079307@hotmail.com

Jie He
School of Transportation, Southeast University
No.2, Sipailou, Nanjing 210096, China
Tel: 86-25-83795284
Mobile: 86-13951018974
Fax: 86-25-83795284
E-mail: hejie@seu.edu.cn

Mark King
Centre for Accident Research and Road Safety - Queensland, Queensland University of Technology
130 Victoria Park Rd, Kelvin Grove, QLD 4059, Australia
Tel: 61-731384546
Mobile: 61-405534183
Fax: 61-731380111
E-mail: mark.king@qut.edu.au

Hongchao Liu
Department of Civil & Environmental Engineering, Texas Tech University
Lubbock, TX 79409, USA
Tel: 806-7423523
Fax: 806-7424168
E-mail: hongchao.liu@ttu.edu

Weihua Zhang
School of Transportation Engineering, Hefei University of Technology
193 Tunxi Rd, Hefei 230009, China
Tel: 86-551-2901960
Mobile: 86-18905699179
Fax: 86-551-2901960
E-mail: ahweihua@163.com

Word count: Text (5614)+Tables and figures (7) = 7364
Submission date: July 29, 2012
Abstract

The effects of suspension parameters and driving conditions on dynamic load-sharing of longitudinal-connected air suspensions of a tri-axle semi-trailer are investigated in this study. A novel nonlinear model of a multi-axle semi-trailer with longitudinal-connected air suspensions is formulated based on fluid mechanics and thermodynamics and validated through test results. The effects of road surface conditions, driving speeds, air line inside diameter and connector inside diameter on dynamic load-sharing capability of the semi-trailer were analyzed in terms of load-sharing criteria. Simulation results indicate that, when larger air lines and connectors are employed, the DLSC (Dynamic Load-Sharing Coefficient) optimization ratio reaches its peak value when the road roughness is medium. The optimization ratio fluctuates in a complex manner as driving speed increases. The results also indicate that if the air line inside diameter is always assumed to be larger than the connector inside diameter, the influence of air line inside diameter on load-sharing is more significant than that of the connector inside diameter. The proposed approach can be used for further study of the influence of additional factors (such as vehicle load, static absolute air pressure and static height of air spring) on load-sharing and the control methods for multi-axle air suspensions with longitudinal air line.

Key words: Dynamic load-sharing; Longitudinal-connected air suspensions; Multi-axle; Semi-trailer
1 INTRODUCTION

Extensive studies of “road-friendly” heavy vehicles have been performed during the last few decades to reduce road damage and increase the rated load of vehicles. However, the load-sharing ability of multi-axle heavy vehicles, which has a strong correlation with road friendliness, has been far from adequately investigated. Load-sharing is defined as the equalization of the axle group load across all wheels/axles (1). When a multi-axle heavy vehicle with leaf suspensions travels on a rough road or hits a bump or a pothole, such as a bridgehead, or speed control humps, unequally distributed loads among the axles of an axle group are often observed due to the ineffectiveness of the load-sharing mechanism (centrally pivoted walking beam, trunnion shaft, etc) and the high stiffness of leaf springs (2). This phenomenon causes overloading of a single axle of the axle group, which has at least two disadvantages: (a) it increases the possibility of a tire bursting as well as reducing the maneuverability and stability of the vehicle. (b) it accelerates the rutting and fatigue that contributes to pavement damage (3). As a consequence, the improvement of load-sharing within axle group has attracted much attention from vehicle manufacturers and road management departments.

Load-sharing performances of axle groups are specified in regulations for road-friendly vehicles in many countries. The DIVINE (Dynamic Interaction between Vehicle and Infrastructure Experiment) project undertaken by OECD (Organization for Economic Cooperation and Development) countries suggest that to qualify as a road-friendly tandem suspension, the average load variation per unit of relative vertical suspension displacement must be less than 0.3KN/mm (4). The Australian specification for road-friendly suspensions nominates that road-friendly suspensions must have static load-sharing, i.e., load-sharing when the vehicle is static, to a defined value, between axles in an axle group or tires in an axle group, but the formal methodology to determine the static load-sharing value on an heavy vehicle was not defined (5). In Europe, an air suspension needs to have fully-functioning hydraulic shock absorbers to pass a static road-friendliness test (6), and heavy vehicles with road-friendly suspensions are allowed higher static axle loads. A common problem for these regulations is that they only specify the static load-sharing of vehicles, there is no requirement for suspensions to retain their dynamic load-sharing performance, i.e., load-sharing when the vehicle is driving.

Many load-sharing metrics have also been proposed by researchers. LSC (Load-Sharing Coefficient) and DLSC (Dynamic Load-Sharing Coefficient) have been used to evaluate static and dynamic load-sharing, respectively (7, 8). Noting that perfect load equalization would give an LSC of 1.0 (9), LSC values for steel suspensions were documented in the range 0.791 to 0.957 (7). Air suspensions with conventional-size longitudinal air lines were placed in the middle of this range with LSCs of 0.904 to 0.925 (10). More recent studies commissioned by the National Road Transport Commission of Australia found that installation of larger air lines on multi-axle air suspensions increased longitudinal air flow between axles (11). Follow-up tests funded by the Queensland Department of Main Roads discovered that an improvement in DLSC of 4–30% for a tri-axle coach and 37–77% for a tri-axle semi-trailer were obtained by alternating the conventional-size longitudinal air connection (three 6.5 mm inside diameter connectors connecting a 6.5 mm inside diameter air line) with larger air connection (three 20 mm inside diameter connectors connecting a 50 mm inside diameter air line) (12). However, due to the limitations of laboratory equipment, only vehicle speed and a limited number of inside diameters of air line were considered in most tests, the effect of key air suspension parameters such as air line inside diameter, connector inside diameter, static absolute air pressure and static air spring height, and driving conditions (vehicle speed, road class) on load-sharing have not yet been investigated comprehensively.

Limitations of laboratory and on-road tests can be addressed by developing realistic models of longitudinal-connected air suspensions. Potter et al developed a simplified tandem bogie model, and by changing the damping coefficient and torsional stiffness of the leveling beam of the model (2), it can represent load-leveling steel suspensions, independent steel suspensions, longitudinal-connected
air suspensions, and independent air suspensions, respectively. Lloyd proposed a model of a tri-axle semi-trailer with longitudinal-connected air suspensions, and used a variable named “load-sharing fraction” to represent the load-sharing ability of the suspension. However, the physical meaning of the variable was unclear (13). A more realistic model of a similar type of tri-axle semi-trailer was developed by Roebuck et al based on aerodynamics and thermodynamics (14). In the model, the volumetric flow rate (m³/s) between two air springs was assumed to be simply proportional to the difference in air pressure with a constant coefficient – \( C_{\text{flow}} \) (m³/Kpa.s); in addition, the volumes and effective areas of the air springs were simplified as constants while the vehicle was travelling.

Unfortunately these simplifications of nonlinearities reduced the precision of the proposed models. A more realistic model of longitudinal-connected multi-axle air suspensions is urgently needed for precise analysis and optimization of load-sharing in multi-axle semi-trailers.

The rest of this paper is organized in the following order. In Section 2, a novel nonlinear model of longitudinal-connected tri-axle air suspensions is derived based on fluid mechanics and thermodynamics. The accuracy of the model is validated and load-sharing criteria are chosen in Section 3. Based on the model, the effects of some key air suspension parameters (inside diameter of air line and connector) and driving conditions (vehicle speed and road class) on dynamic load-sharing are analyzed in Section 4. Finally, Section 5 presents a summary of the results and draws some conclusions.

2 INTEGRATED MODEL OF VEHICLE AND ROAD EXCITATION

2.1 Mathematic model of the tri-axle semi-trailer

A basic half model representing a typical tri-axle semi-trailer with longitudinal-connected air suspensions in most western countries was employed, as shown in Figure 1. This model includes 4 degrees of freedom (DOF), which are vertical displacement of sprung mass and three unsprung masses, \( z, \ x_1, \ x_2, \ x_3 \).

![FIGURE 1 Schematic of the tri-axle semi-trailer with longitudinal-connected air suspensions](image)

The equations of motion of the semi-trailer are given by:

\[
m_1\ddot{x}_1 = (q_1 - x_1)k_{s1} + c_1(z - \dot{x}_1) - (P_{s1} - P_{s2})A_{s1} + \frac{1}{3}mg \tag{1}
\]

\[
m_2\ddot{x}_2 = (q_2 - x_2)k_{s2} + c_2(z - \dot{x}_2) - (P_{s2} - P_{s3})A_{s2} + \frac{1}{3}mg \tag{2}
\]

\[
m_3\ddot{x}_3 = (q_3 - x_3)k_{s3} + c_3(z - \dot{x}_3) - (P_{s3} - P_{s4})A_{s3} + \frac{1}{3}mg \tag{3}
\]

\[
m\dddot{z} = (P_{s1} - P_{s2})A_{s1} + (P_{s2} - P_{s3})A_{s2} + (P_{s3} - P_{s4})A_{s3} - c_1(z - \dot{x}_1) - c_2(z - \dot{x}_2) - c_3(z - \dot{x}_3) - mg \tag{4}
\]

Where \( m_1, m_2, m_3 \) and \( q_1, q_2, q_3 \) are the unsprung mass and road excitation of the three axles, respectively. \( m \) is the sprung mass of the semi-trailer. \( J \) is the moment of inertia of the gross...
sprung mass around the lateral axis. \( P_1, P_2, P_3 \) and \( A_1, A_2, A_3 \) are the dynamic absolute pressure and the dynamic effective area of the three air springs, respectively. \( P_0 \) is atmospheric pressure. \( l \) is the wheelbase, \( c_1, c_2, c_3 \) are the damping coefficients of three dampers, and \( k_1, k_2, k_3 \) are the stiffness of the three tires.

### 2.2 Road roughness excitation

Many methodologies have been proposed to model road surface profile \((15, 16)\). One method is to describe the profile as a realization of a random process that is represented by its PSD (power spectral density). A concise spectral model is used in this study as \((17)\):

\[
G_s(n) = G_s(n_0)(n/n_0)^{-2} \quad (n_0 < n < n_z)
\]

where \( G_s(n) \) is the PSD function \((m^3/cycle)\) for the road surface elevation; \( n \) is the spatial frequency \((cycle/m)\); \( n_0 \) is the reference spatial frequency, \( n_0 = 0.1 \) cycle/m; and \( G_s(n_0) \) is the roughness coefficient \((m^3/cycle)\), whose value is chosen depending on the road condition. In this study, classification of road roughness is based on the index of the International Organization for Standardization (ISO 1995) \((18)\). The ISO has proposed a road roughness classifications from Class A (very good) to Class H (very poor) according to different values of \( \phi(n_0) \). \( n_1 \) and \( n_2 \) are lower and upper spatial cutoff frequencies when \( G_s(n) \) reaches 1 m\(^3\)/cycle and 10\(^{-5}\) m\(^3\)/cycle, respectively \((18)\).

Then the road roughness \( q(t) \) is derived as follow based on methods described in references \((19)\) and \((20)\):

\[
q(t) = -2\pi n_0 u q(t) + 2\pi n_0 \sqrt{G_s(n_0)} w(t)
\]

Where \( u \) is vehicle speed, \( w(t) \) is a white noise whose power is 1. The upper cutoff frequency \( n_2 \) was modeled by setting the sampling frequency of \( w(t) \) based on Nyquist sampling theory, i.e., the sampling frequency should be at least \( 2n_2u \) Hz. A time delay of \( 1/v \) for road excitation is applied between adjacent axles.

### 2.3 Detailed model of longitudinal-connected tri-axle air suspensions

To solve the equations in Section 2.1, a detailed model of longitudinal-connected tri-axle air suspensions is needed to express \( P_1, P_2, P_3 \) as functions of the 5 variables (5 DOF).

It is assumed that all the air springs are stroked fast enough such that all of the heat of the operation is conserved when the vehicle is travelling, i.e., an adiabatic process occurs. Thus, the formula for calculating the dynamic absolute air pressure inside the front air spring, \( P_1 \), is \((21)\):

\[
P_1 = \frac{V_{1s}}{m_{1s}} = \text{constant}
\]

\( V_{1s}, V_{310} \) are the dynamic volume and static volume of the front air spring. \( m_{1s}, m_{310} \) are the dynamic air mass, and static air mass inside the front air spring. \( P_{310} \) is the static absolute air pressure inside the front air spring. The value of the above exponent, \( k \), varies with the gas used and is a function of the specific heat of the gas. Air suspension operation is characterized by neither an isothermal nor an adiabatic process, but is polytropic. In normal use, however, the process is much closer to adiabatic than isothermal. Accordingly the value of \( k \) is set to 1.4. \( P_1 \) is obtained from equation \((13)\) as follows:

\[
P_1 = \left( \frac{V_{1s}m_{1s}}{V_{310}m_{310}} \right)^{1/k} P_{310}
\]

Where \( V_{1s} \) is a function of dynamic height of the front air spring, and is given by
\[ V_{s1} = (z - x_l - \phi l) A_{s1} + V_{s10} \]  \tag{9}

Where \( A_{s1} \) can also be approximated as a function of dynamic height of the front air spring based on experimental data.

\( m_{s1} \), depends on the air flow between the front air spring and the longitudinal air line, i.e., the air flow inside the front connector, is given by

\[ m_{s1} = m_{s0} + \int_0^t G_1 dt \]  \tag{10}

Where \( G_1 \) denotes the air flow rate inside the front connector (kg/s). Since only small variations of temperature, air pressure and air spring volume exist when the semi-trailer is travelling, the air flow is considered to be an incompressible steady flow (22), which satisfies the following formula, according to Bernoulli’s equation (22):

\[ \frac{P_1}{\rho} + \frac{1}{2} V_{f1}^2 = \frac{P_1}{\rho} + \frac{1}{2} V_{f1}^2 \]  \tag{11}

Where \( P_1 \) is the dynamic absolute air pressure inside the front connector. \( v_{f1} \), \( v_{f1} \) are the air flow speed (m/s) inside the front air spring and the front connector, respectively; the air inside all the air springs, connectors and the air line is assumed to have a same constant density, \( \rho \), when the semi-trailer is travelling. \( A_{f1} \) is the effective area of the front connector, which is equal to the actual area multiplied by a contraction coefficient, 0.7 (23).

Noting that \( A_{s1} \) is related to \( A_{f1} \) because \( A_{s1} v_{s1} = A_{f1} v_{f1} \), inserting \( v_{s1} = A_{f1} v_{f1} / A_{s1} \) into equation (11) yields

\[ v_{f1} = \sqrt{\frac{2}{\rho} \left[ \frac{P_1}{P_1} - P_{f1} \right] \left[ 1 - \left( \frac{A_{f1}}{A_{s1}} \right)^2 \right]} \]  \tag{12}

\( v_{f1} \) is modified with a coefficient, \( c_d \) (0.8), to reflect the friction in the connector. Therefore, the actual air flow speed inside the front connector, \( v'_{f1} \), and \( G_1 \) are given by

\[ v'_{f1} = c_d \sqrt{\frac{2}{\rho} \left[ \frac{P_1}{P_1} - P_{f1} \right] \left[ 1 - \left( \frac{A_{f1}}{A_{s1}} \right)^2 \right]} \]  \tag{13}

\[ G_1 = \text{sgn}(P_1 - P_{s1}) c_d A_{f1} \sqrt{2 \rho} \left| P_{s1} - P_{f1} \right| \left[ 1 - \left( \frac{A_{f1}}{A_{s1}} \right)^2 \right] \]  \tag{14}

Substituting equations (9), (10) and (14) into equation (8) yields

\[ P_{s1} = P_{s10} \left[ \frac{m_{s0} + \int_0^t \text{sgn}(P_1 - P_{s1}) c_d A_{f1} \sqrt{2 \rho} \left| P_{s1} - P_{f1} \right| \left[ 1 - \left( \frac{A_{f1}}{A_{s1}} \right)^2 \right] dt}{(z - x_l - \phi l) A_{s1} + V_{s10} m_{s10}} \right]^4 \]  \tag{15}

The dynamic absolute air pressures inside the three connectors and the longitudinal air line are assumed to have the same value, \( P_{f1}, \) during travel. Thus, similar expressions for the air flow rate inside the middle and rear connectors (\( G_2 \) and \( G_3 \)), as well as the dynamic absolute air pressure inside the middle and rear air springs (\( P_{s2} \) and \( P_{s3} \)) are derived as

\[ G_{2,3} = \text{sgn}(P_1 - P_{s2,3}) c_d A_{f2,3} \sqrt{2 \rho} \left| P_{s2,3} - P_{f1} \right| \left[ 1 - \left( \frac{A_{f2,3}}{A_{s2,3}} \right)^2 \right] \]  \tag{16}
\[
V_{s2,3} = \frac{P_{20,30}}{V_{s0} + \int_{0}^{t} \text{sgn}(P_{r1} - P_{2,3})c_{d}A_{f2,3} \sqrt{2\rho \left| P_{2,3} - P_{r1} \right| \left(1 - \left(\frac{A_{f2,3}^2}{A_{f2,3}^2}\right)\right)} dt} \left[(z - x_{2,3})A_{2,3} + V_{s20,30}\right] m_{s2,3} \]
\] (17)

Where \( P_{20,30}, V_{s20}, m_{s20} \) are the static absolute air pressure, static volume and static air mass of the middle air spring, \( P_{30,30}, V_{s30}, m_{s30} \) are the corresponding parameters for the rear air spring; and \( A_{f3} \) are the areas of the middle and rear connectors, respectively. The three air springs have the same static absolute air pressure, static volume and static air mass, and the three connectors have the same inside diameter.

The volume of the air line is constant because the air line is made of steel. Based on equation (8), the dynamic absolute air pressure inside the air line, \( P_{r1} \), is expressed as a function of the static air mass of the air line, \( m_{s0} \), the static absolute air pressure inside the air line, \( P_{s10} \), and the gross air flow rate inside the air line, \( G_{s} \), shown as follows:

\[
P_{r1} = \left(\frac{m_{s0} + \int_{0}^{t} G_{s} dt}{m_{s0}}\right)^{1.4} P_{s10}
\] (18)

\[
G_{s} = -G_{1} - G_{2} - G_{3}
\] (19)

Substituting equations (14), (16) and (19) into equation (18) yields:

\[
P_{r1} = m_{s0}^{-1.4} P_{s10} m_{s0} + \left[\text{sgn}(P_{r1} - P_{2,3})c_{d}A_{f2,3} \sqrt{2\rho \left| P_{2,3} - P_{r1} \right| \left(1 - \left(\frac{A_{f2,3}^2}{A_{f2,3}^2}\right)\right)} \right] \left[1 - \left(\frac{A_{f2,3}^2}{A_{f2,3}^2}\right)\right] - \text{sgn}(P_{r1} - P_{3,3})c_{d}A_{f3} \sqrt{2\rho \left| P_{3,3} - P_{r1} \right| \left(1 - \left(\frac{A_{f3}^2}{A_{f3}^2}\right)\right)} dt^{1.4}
\] (20)

Based on the equations in Section 2.1, Section 2.2 and equations (15), (17) and (20), an integrated model of road excitation and a fully-loaded tri-axle semi-trailer with longitudinal-connected air springs was developed with Matlab/Simulink. Parts of the key parameters are tabulated in Table. 1. The expression of the effective area of each air spring as a function of the dynamic height of corresponding air spring will be obtained based on test results in Section 3.2.
TABLE 1 Parameters of the Tri-axle Semi-trailer Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{s10}$</td>
<td>0.0783</td>
<td>m²</td>
<td>Static effective area of each air spring</td>
</tr>
<tr>
<td>$V_{s10}$</td>
<td>0.0125</td>
<td>m³</td>
<td>Static volume of each air spring</td>
</tr>
<tr>
<td>$h_{s}$</td>
<td>0.16</td>
<td>m</td>
<td>Static height of each air spring</td>
</tr>
<tr>
<td>$d_f$</td>
<td>0.0065</td>
<td>m</td>
<td>Inside diameter of each connector</td>
</tr>
<tr>
<td>$d_s$</td>
<td>0.0065</td>
<td>m</td>
<td>Inside diameter of the longitudinal air line</td>
</tr>
<tr>
<td>$P_{s10}$</td>
<td>464288</td>
<td>Pa</td>
<td>Static absolute air pressure inside each air spring, each connector and the air line</td>
</tr>
<tr>
<td>$P_0$</td>
<td>101325</td>
<td>Pa</td>
<td>Atmospheric pressure</td>
</tr>
<tr>
<td>$m$</td>
<td>8700</td>
<td>kg</td>
<td>Gross sprung mass of the semi-trailer</td>
</tr>
<tr>
<td>$m_{t1}$</td>
<td>336</td>
<td>kg</td>
<td>Unsprung mass of each air spring</td>
</tr>
<tr>
<td>$J$</td>
<td>5684</td>
<td>kg.m²</td>
<td>Moment of inertia of the gross sprung mass around the lateral axis</td>
</tr>
<tr>
<td>$k_{s1}$</td>
<td>1960000</td>
<td>N/m</td>
<td>Stiffness of dual tires on each hub</td>
</tr>
<tr>
<td>$\rho$</td>
<td>6.5417</td>
<td>kg/m³</td>
<td>Density of air inside air springs, air connectors and the air line</td>
</tr>
<tr>
<td>$c_{\text{rebound}}$</td>
<td>288600</td>
<td>N.s/m</td>
<td>Damping coefficient of each damper when dynamic height of respective suspension is increasing</td>
</tr>
<tr>
<td>$c_{\text{bump}}$</td>
<td>184500</td>
<td>N.s/m</td>
<td>Damping coefficient of each damper when dynamic height of respective suspension is decreasing</td>
</tr>
</tbody>
</table>

3 LOAD-SHARING CRITERIA AND MODEL VALIDATION

3.1 Load-sharing criteria

Criteria need to be determined to evaluate the load-sharing of the semi-trailer. A metric often used to characterize the magnitude of dynamic forces of a wheel in an axle group is the Dynamic Load Coefficient (DLC) (7), defined as

$$\text{DLC}(i) = \frac{\sigma_i}{F_{\text{mean}}(i)}$$

(29)

Where $\sigma_i$ = the standard deviation of wheel-force $i$, and $F_{\text{mean}}(i)$ = the mean wheel-force of wheel $i$. Although DLC is usually referred to as a road-friendliness criterion and has been criticized for its mutually exclusivity with another load-sharing criterion, LSC ($J$), it still has been widely used as one measure to differentiate suspension types from each other (e.g., steel vs. air) (12, 13). In addition, Pont points out that LSC does not address dynamic load-sharing. The DLSC was proposed as an alternative to LSC, to account for the dynamic nature of wheel-forces and instantaneous load-sharing during travel (8), and is defined as

$$\text{DLSC}_i = \left( \frac{\sum_{j=1}^{n} (\text{DLS}_j(i) - \frac{1}{k} \sum_{j=1}^{n} \text{DLS}_j(i))^2}{k} \right)^{\frac{1}{2}}$$

(30)

The dynamic load-sharing of wheel $i$, $\text{DLS}_j(i)$, is

$$\text{DLS}_j(i) = \frac{nF_j(i)}{\sum_{i=1}^{n} F_j(i)}$$

(31)

Where $n$ is the number of wheels on one side of an axle group; $k$ is the number of terms in the
dataset; and \( F_i(j) \) is the instantaneous force at wheel \( i \).

In this study, both the average DLC and the average DLSC of tires on the same side of the semi-trailer axle group were employed for analysis of the simulation results.

3.2 Model validation

The prototype of the tri-axle semi-trailer was tested for verification of the model, as shown in Figure 2. The tests were parts of a joint project titled “Heavy vehicle suspensions – testing and analysis” between Queensland University of Technology (QUT) and the Department of Transport and Main Roads, Queensland (TMR) (13).

The setups of the tests are shown in Figure 2. Two types of longitudinal connections were used to connect the air springs on the same side: conventional (three 6.5 mm inside diameter connectors connecting a 6.5 mm inside diameter air line) and large (three 20 mm inside diameter connectors connecting a 50 mm inside diameter air line). Strain gauges (one per hub) were mounted on the neutral axis of each axle between the spring and the hub to record the shear force on the hubs, i.e., air spring force, and accelerometers were mounted as closely as possible to each hub and to the corresponding upper positions at the chassis to derive the dynamic height of each air spring. In addition, six air pressure transducers were employed to obtain the pressures inside the air springs, and a TRAMANCO P/L on-board CHEK-WAY telemetry system was used to record all the data.
The dynamic force of each tire was calculated from the shear force on the respective hub and the acceleration on the respective axle. The effective area of each air spring was obtained by dividing the respective shear force by the respective pressure inside the air spring, and the volume of each air spring was derived by multiplying the respective effective area by the respective spring height.

The tests comprised of driving the semi-trailer over three typical urban road sections at speeds ranging from 60 km/h to 80 km/h; the sections of road varied from smooth with long undulations to rough with short undulations. The \( IRI \) (International Roughness Index) values of each road section were provided by TMR, and \( IRI \) is related to \( G_s(n_s) \) in equation (6) as

\[
IRI = 0.78 \times 10^3 \sqrt{G_s(n_s)} \quad (24).
\]

Ten seconds of dynamic signal data were recorded per road section, and this was done for both experimental cases (i.e., conventional longitudinal connection vs. large longitudinal connection) for the fully loaded condition.

Thus, the effective area of each air spring is approximated as a function of the dynamic height of corresponding air spring, \( y \), based on the experimental results, shown as:

\[
A_s = -7.670500y^2 + 2.866880y - 0.354226y - 0.093002 \quad (32)
\]

The effective area multiplied by the dynamic spring height yields:

\[
V_s = -7.670500y^3 + 2.866880y^2 - 0.354226y + 0.093002y \quad (33)
\]

The comparisons between the test and simulation results in terms of load-sharing performance are listed in Table 2.
### TABLE 2 Comparison of Load-Sharing Performances between Tests and Simulations

<table>
<thead>
<tr>
<th>Test/simulation number</th>
<th>Type of longitudinal connection</th>
<th>IRI</th>
<th>Velocity (km/h)</th>
<th>Load-sharing criteria</th>
<th>Error ratio (compared with the test results)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>conventional</td>
<td>6.213</td>
<td>60</td>
<td>DLC</td>
<td>0.0791 vs 0.0734, -7.2%</td>
</tr>
<tr>
<td>2</td>
<td>large</td>
<td>6.213</td>
<td>60</td>
<td>DLSC</td>
<td>0.0505 vs 0.0432, -14.5%</td>
</tr>
<tr>
<td>3</td>
<td>conventional</td>
<td>7.602</td>
<td>70</td>
<td>DLSC</td>
<td>0.1034 vs 0.1003, -3.0%</td>
</tr>
<tr>
<td>4</td>
<td>large</td>
<td>7.602</td>
<td>70</td>
<td>DLC</td>
<td>0.0851 vs 0.0722, -15.2%</td>
</tr>
<tr>
<td>5</td>
<td>conventional</td>
<td>8.880</td>
<td>80</td>
<td>DLSC</td>
<td>0.1773 vs 0.1680, -5.2%</td>
</tr>
<tr>
<td>6</td>
<td>large</td>
<td>8.880</td>
<td>80</td>
<td>DLC</td>
<td>0.1506 vs 0.1258, -16.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DLSC</td>
<td>0.1474 vs 0.1258, -14.7%</td>
</tr>
</tbody>
</table>

As shown in Table 2, a reasonable agreement exists between test and simulation results for both types of connection, under various road roughness conditions and vehicle speeds. The absolute error ratios of the DLC are less than 10% for all the tests and simulations; except for test/simulation 4, the absolute error ratios of the DLSC are less than 20% for all the other tests/simulations. It is also noted that all the simulation values of criteria are smaller than the corresponding test values, which is mainly due to wear of the suspensions of the test vehicle after a period of use and the ignorance of the coupling between the prime mover and the semi-trailer.

It can be concluded that the simulation results correlated well with the measurements in terms of both DLC and DLSC. Therefore, the integrated model of vehicle and road excitation in this study can be employed for further analysis.

## 4 EFFECT OF DRIVING CONDITIONS AND SUSPENSION PARAMETERS ON LOAD-SHARING

### 4.1 Effect of road roughness

The effects of road roughness on load-sharing were studied assuming the semi-trailer was fully-loaded with a constant vehicle speed of 20m/s. Two types of connections among air suspensions were considered, i.e., type “1” (three 6.5 mm inside diameter connectors connecting a 6.5 mm inside diameter air line) and type “2” (three 50 mm inside diameter connectors connecting a 50 mm inside diameter air line). The influence of road roughness (IRI varies from 2 to 9, representing road classes from A to C) on the average DLSC and the average DLC are shown in Figure 3.
Figure 3 (a) indicates that as the IRI increases, the average DLSC increases for both types of air suspensions. When the IRI increases from 2 to 11, the average DLSC of the semi-trailer with connection “1” increases from 0.0053 to 0.1559, and the average DLSC of the semi-trailer with connection “2” increases from 0.0049 to 0.1601. The reason for this phenomenon is that as the road roughness increases, the peak value of tire force increases, so it becomes more difficult for the air suspension to distribute the loads equally among all axles. Similar with the DLSC, the average DLC generally increases as IRI increases, as shown in Figure 3 (b), except for a reduction when IRI is 9. This phenomenon indicates that although there are correlations between the two criteria, the load-sharing performance criterion -- DLSC, is not always in accordance with the road-friendliness performance criterion -- DLC.

The effect of road roughness on optimization ratios for load-sharing is shown in Figure 3 (c). It is evident that the optimization ratio for DLSC does not necessarily increase or decrease as the IRI increases. When the IRI increases from 2 to 4, and then to 11, the optimization ratio for DLSC increases from 7.6% to 15.3% before declining to -2.7%. This phenomenon is further complicated by the fact that the main frequencies of the road profile excitations change with the roughness. When the IRI is low, most undulations are relatively long and accordingly low frequency road excitations are prominent, and are even lower than the transmission frequency of the air in connection “2”, so a low DLSC optimization ratio is observed at first. As the IRI increases, the lower cut-off frequency of road excitation increases and more excitations reach the air transmission frequency, thus the DLSC optimization ratio climbs until it reaches a peak value. As the dominant frequencies of road excitations continue to increase, air transmission becomes not fast enough to distribute loads equally among axles under the high frequency road excitations, the optimization ratio thus begins to decline, and even reaches a negative value.

The DLC optimization ratio in Figure 3 (c) fluctuates more than the DLSC optimization ratio, with the most obvious difference being that the DLC optimization ratio increases again when the IRI exceeds 11.
4.2 Effect of vehicle speed

Vehicle speeds varying from 20 km/h to 90 km/h were considered for simulations of the fully-loaded semi-trailer with standard “A” class road excitations.

The influence of speed on load-sharing is illustrated in Figure 4. As the speed increases from 20 km/h to 90 km/h, load-sharing of the semi-trailer with both types of air line deteriorates. The DLSC increases from 0.0041 to 0.0186, 0.0029 to 0.0160 for the semi-trailer with connections “1” and “2”, respectively. The DLC increases from 0.0050 to 0.0375, and from 0.0039 to 0.0338 for the semi-trailer with connections “1” and “2”, respectively.

As shown in figure 4 (c), the DLSC optimization ratio fluctuates with vehicle speed. When vehicle speed increase from 20 km/h to 40 km/h, and then to 70 km/h, the DLSC optimization ratio decreases rapidly from 30.1% to 11.6% before increasing slowly to 15.3%. It then declines to 14.3% at 90 km/h. Similar changes in the DLC optimization ratio are found when speeds are less than 30 km/h, after which the DLC optimization ratio increases gradually.

A reasonable explanation for the patterns of DLSC and DLC optimization ratios is that the vehicle speed affects the product of the vehicle speed and the cutoff values of the roughness spatial frequency, i.e., \( w_1 \) and \( w_2 \), which means higher vehicle speed results in higher upper and lower cut-off frequencies, as well as a wider frequency band. These changes have a complex influence on the transmission response of air and the dynamic stiffness of each air spring.

4.3 Effects of size of air line and connector

The effects of size of air line and connector on load-sharing are plotted in Figure 5, with a constant vehicle speed of 20 m/s for the fully-loaded semi-trailer and a standard “B” class road profile. The inside diameters of the connectors are always less than or equal to those of the air lines in the simulations.
1. It can be seen in Figure 5 (a) and Figure 5 (b) that with a fixed inside diameter air line, both DLSC and DLC reduce quickly as the connector inside diameter increases from 10 mm to 30 mm. For example, with a 100 mm inside diameter air line, reductions up to 11.5% and 8.4% are observed in DLSC and DLC, respectively. When the inside diameter of air line increases beyond 30 mm, both DLSC and DLC decrease more slowly and become constants.

2. However, the change in DLSC with air line inside diameter is different from that of the DLC, when the inside diameter of the connector is fixed. With a 10 mm inside diameter connector, as the air line inside diameter increases from 10 mm to 100 mm, the DLSC only decreases 1.0%, while the DLC decreases 6.9%. Thus, although the load-sharing of the semi-trailer improves very slowly by increasing the size of the connector, the dynamic tire force and accordingly the road-friendliness of the semi-trailer are effectively improved.

5 CONCLUSION

4. In this study, the effects of suspension parameters and driving conditions on dynamic load-sharing of longitudinal-connected air suspensions of a tri-axle semi-trailer are investigated comprehensively. A nonlinear model of longitudinal-connected tri-axle air suspensions is formulated based on fluid mechanics and thermodynamics and validated through test results. The effects of road surface conditions, driving speeds, and the air line inside diameters and connector inside diameters on the dynamic load-sharing capability of the semi-trailer were analyzed in terms of the DLSC and DLC, and the following conclusions can be drawn:

- Although there are correlations between the two criteria, the road-friendliness performance criterion--DLC, is not always in accordance with the load-sharing performance criterion--DLSC.

- Through the use of larger air line and connectors, the load transfers more quickly and effectively among axles, thus load-sharing and road-friendliness are improved. Besides, assuming that the inside diameter of the air line is always larger than that of the connector, the influence of the air line inside diameter is more significant than that of the connector.

- The DLSC optimization ratio by employing larger air lines and connectors varies as the road roughness or vehicle speed changes. The lower and upper cut-off frequencies of road excitation changes with the IRI and vehicle speed, which has a complicated impact on air transmission between air bags and thus the damping of the each air bag.

- Compared with previous works based on experimental analysis only, modeling of the tri-axle semi-trailer with longitudinal-connected air suspensions enables a better understanding of the dynamic effects of the truck to explain changes of load-sharing with driving conditions.

This study only considered four factors: road roughness, driving speed, air line inside...
Yikai Chen, Jie He, Mark King, Hongchao Liu, Weihua Zhang

Based on the proposed model, investigation of the influence of more additional factors (such as the static absolute air pressure inside the air spring, static spring height, and vehicle load) on load-sharing, as well as the control of the dampers for further improvement of load-sharing will be undertaken in the future.

Although the vehicle tested was a typical truck used in Australia, the modeling method is applicable to any multi-axle truck with longitudinal-connected air suspension and the simulation results are instructive for design of similar trucks. With the support of these foundations, future work will also focus on the modeling and testing of longitudinal-connected trucks in China.

ACKNOWLEDGEMENT:

This work was supported by the National Natural Science Foundation of China (Grant Nos. 51078087, 51178158 and 51075112), and the Natural Science Foundation of Anhui Province (Grant No. 11040606Q39). The assistance of Dr Lloyd Davis from the Department of Transport and Main Roads, Queensland is also greatly acknowledged.

REFERENCES:


(13) Lloyd E. D. Heavy vehicle suspensions- Testing and analysis. Ph.D. dissertation, Queensland
University of Technology, Brisbane, Australia, 2010.


