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ABSTRACT
Evaluating heavy truck suspensions for road friendliness and ride quality is a complex challenge An experimental study has been conduced to explore various options for evaluating suspension performance The methods examined use laboratory equipment and focus on evaluating suspension performance without the influence of the whole vehicle The experimental program found that "in phase sinusoidal frequency sweep" of constant amplitude produced clear differentiation of suspension response

INTRODUCTION
This paper examines methods for assessing suspension dynamic performance pertaining to the attributes of "road friendliness" and "vertical ride quality" Suspension road friendliness refers to the ability of a suspension to isolate the vehicle from road unevenness so that the dynamic wheel loading imparted to the road is minimized Ride quality is not directly linked to road friendliness, therefore asymmetric viscous damping is necessary to achieve a balance between ride quality and dynamic road loading (1, 2) Suspension spring rate and lack of coulomb damping are important factors for achieving improved overall suspension vertical dynamic performance (3-8)

The methods of assessment described in this paper are the result of research conducted in support of the Paris based Organization of Economic Co-operation and Development OECD DIVINE project (9) This international research project is examining the issues of heavy truck dynamic loading including the effects on bridge and pavement life The research into suspension measurement techniques has focused on the measurement of suspension characteristics rather than the dynamic behavior of the whole vehicle unit It is intended as a means of objectively assessing the performance of a given suspension unit free from vehicle design influences such as wheelbase filtering In this way vehicle designers can choose a suspension of known ride and road-friendlines characteristics

With such an approach, specific suspension models could qualify as road-friendly, leading to the assumption that if a suspension is found to be road-friendly as a unit (i e having certain favorable dynamic characteristics) then most vehicles that use this suspension will be road-friendly

DESCRIPTION OF EXPERIMENTS

The experiments were designed and the results analyzed by Roaduser Research under contract to the National Research Council of Canada (NRC) The experiments were performed on the NRC 4-post shaker A special purpose fabricated test trailer was used as shown in Figure 1 It was constrained at the king pin to eliminate any vertical displacement of the front end, and was loaded in such a way that the mass center was positioned as close as possible to the geometric center of the suspension The three generic tandem axle suspensions tested were

- rigid trailing arm air suspension,
- 4-spring steel leaf suspension with interleaf friction,
- rubber suspended walking beam suspension

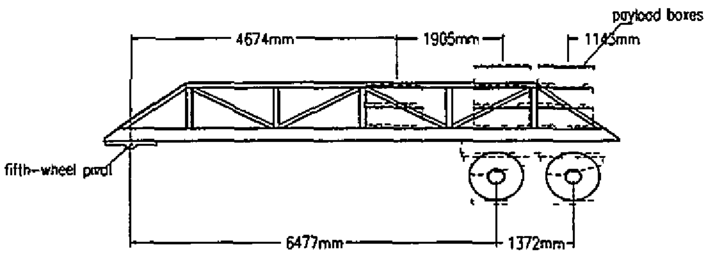

Fig 1 Schematic drawing of test trailer

The test conditions were as follows
Note All tests were conducted with tires inflated to 7 Bar (103 psi)

1) Individual axle loads were fixed at 9,000 kg

2) All 4 wheels of the suspension were supported by actuators

3) Left and right wheels of a common axle were excited with identical signals to eliminate roll

4) Lead and trailing axles were displaced vertically under quasi-static conditions, relative to each other to examine load equalization performance

5) Using displacement mode, the lead and trailing axles were excited in phase with a sinusoidal frequency sweep of DC to 20 Hz

6) Using displacement mode, the lead and trailing axles were excited out of phase with a sinusoidal frequency sweep of DC to 20 Hz

7) Using displacement mode, lead and trailing axles were excited with the IR6 DIVINE Road Profiles representing good, average and poor roads

8) Using displacement mode, lead and trailing axles were excited with a Virtual Road Profile representing good, average and poor roads

9) Using displacement mode, lead and trailing axles were subjected to a simulated drop as individual axles

10) Using displacement mode, lead and trailing axles were subjected to a simulated EC Directive (explained below) drop test ramp at a vehicle speed of 5 km/h

The Council of European Communities have produced a directive which defines what a road friendly suspension is and how it is to be tested Directive 92/7/EEC, (10), is a suspension protocol that applies to all driven axles (either single or bogie axles) and defines road-friendliness with the following component and performance requirements

The axle must have dual tires

- The suspension must use hydraulic dampers The vehicle must have a sprung mass frequency no greater than 2 0 Hz
- Damping ratio (D) of the sprung mass must be more than 20% of critical damping (with dampers fitted)
- The sprung mass must have a damping ratio no more than 50% of D when all dampers are removed

To prove compliance with the test requirement the following methods can be used

- Traverse a specified 80 mm step at 5 km/h and analyze the suspension frequency and damping from the transient time history occurring after the ramp
- Pull down the vehicle chassis so that the driving axle load is 1 5 times its maximum static load value, release the vehicle and analyze the subsequent oscillation
- Pull up the chassis so that the sprung mass is lifted 80 mm above the drive axle, release the vehicle and analyze the subsequent oscillation
- Use some other procedure that has been proven to be a valid procedure

DETAILS OF SUSPENSION TESTS
The tests were performed using the rigid test trailer described previously

Quasi-static load equalization test
With forward and aft shaker stands out of phase by 180 degrees, the road simulator was driven by a sinusoidal drive signal of ± 100 mm at a continuous frequency of 0 2 Hz

In phase sinusoidal frequency sweep
Using constant displacement mode, lead and trailing axles were excited in phase with a continuous sinusoidal excitation sweep The frequency range used was 0 5 Hz to 15 Hz The rate of change of frequency used was 5 Hz per minute Each test was conducted at a constant amplitude throughout the frequency range Where possible the tests were conducted at the following double amplitudes

1, 2, 4, 6, 8, 10, 12 and 14 mm

Out of phase sinusoidal frequency sweep
Using constant displacement mode, the lead and trailing axles were excited at 180 degrees out of

phase with a continuous sinusoidal excitation sweep Frequency range was 0 5 Hz to 20 Hz Rate of change of frequency was 5 Hz per minute

Each test was conducted at a constant amplitude throughout the frequency range Up to 10 tests were performed at the following double amplitudes
1, 2, 4, 6, 8, 10, 12 and 14 mm

DIVINE road profiles (good, average and poor roads)
Using displacement mode, lead and trailing axles were excited with the three DIVINE road profiles The right wheel path profiles were used to drive both the left and right posts of the shaker

The simulated vehicle speeds used were
40, 60, 80,100 and 120 km/h

Virtual road profiles (good, average and poor roads)
Using displacement mode, lead and trailing axles were excited with a virtual road surface (the unevenness characteristic was defined as the slope of -2 of the PSD of the virtual road profile)

The simulated vehicle speeds used were
40, 60, 80,100 and 120 km/h

Simulated Drop Tests
Using displacement mode, lead and trailing axles were subjected to a simulated EC drop test as follows

- simultaneous axle drop (both axles dropped at the same instant)
- single axle drop (only one axle was dropped in a given test)
- sequential axle drop (each axle was dropped in sequence at a simulated speed of 5 km/h with a simulated approach ramp (as shown in figure 2)

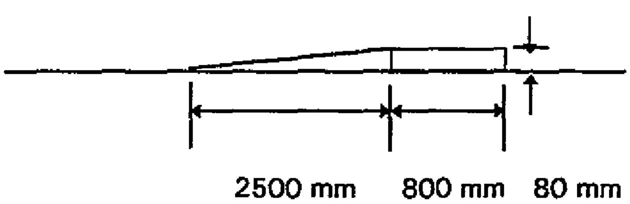

Fig 2 EC suspension test step

EXPERIMENTAL RESULTS

QUASI-STATIC EQUALIZATION AND HYSTERESIS

The assessment of suspension hysteresis was conducted at quasi-static rates over a relative displacement range of ± 100 mm Hysteresis was determined by averaging the force magnitudes at half stroke length (the zero displacement crossing) The general results are contained in Table 1

Table 1 Average hysteresis for suspensions

Suspension Type	Average Hysteresis
Air suspension with dampers	13 86 kN
Air suspension without dampers	12 23 kN
Steel leaf spring	16 63 kN
Rubber sprung walking beam	0 50 kN

Load equalization was evaluated on the basis of average load variation per unit of relative vertical axle displacement The results are contained in Table 2

Table 2 Average load equalization

Suspension Type	Load Equalization
Air suspension	0 367 kN/mm
Steel leaf spring	0 567 kN/mm
Rubber sprung walking beam	0 076 kN/mm

As expected, due to the static equalizing nature of the walking beam, the rubber sprung walking beam suspension exhibited excellent load equalization and hysteresis characteristics The air suspension load equalization was 35% better than that of the steel spring suspension

Quasi-static load equalization is a very important suspension performance attribute because suspensions that equalize axle loads poorly impose consistently higher road distress than suspensions that equalize well

The method of assessment of suspension axle load equalization described above yields technical information that can be used, together with specific vehicle dimensions, to address any suspension equalization requirement

IN PHASE SINUSOIDAL FREQUENCY SWEEP

The in-phase sinusoidal excitation was conducted for a range of constant amplitudes from DC to 20 Hz The continuous frequency sweep was conducted at 5 Hz per minute The various constant single amplitude displacements used were 1, 2, 3, 4, 6, and 8 mm The results clearly show that the input displacement of 1 mm produced superior results, allowing for clear comparison of the sprung and unsprung mass response for all suspensions examined The results of the 1 mm excitation are found in Table 3 The single amplitude peak forces shown occurred at the sprung mass and unsprung mass frequencies The steel spring suspension unsprung mass frequency and force could not be identified because the response was very low

Table 3 Single amplitude peak tire forces at the sprung mass and unsprung mass frequencies resulting from a 1 mm sinusoidal sweep input

Suspension Type	Sprung Mass		Unsprung Mass	
	Freq	Force pk	Freq Hz	Force pk
Air suspension with dampers	1 62 Hz	4 30 kN	12 12	18 93 kN
Air suspension without dampers	1 56 Hz	9 25 kN	11 14	70 46 kN
Steel leaf spring	3 10 Hz	31 86 kN	11 60	20 31 kN
Rubber sprung walking beam	2 54 Hz	29 40 kN	16 39	35 39 kN

Typical plots of axle load response as a function of the constant 1 mm single amplitude for two suspensions are shown in Figures 3 & 4 These plots show sharp differentiation in suspension response at both the sprung and unsprung mass frequencies These results strongly support the use of in phase sinusoidal excitation as a means of assessing suspension road-friendliness

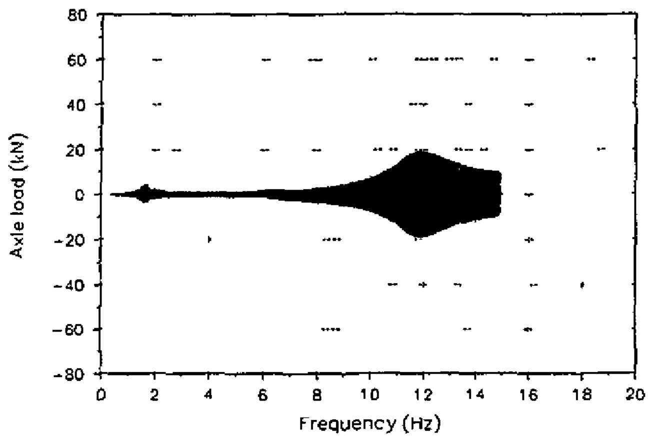

Fig 3 Constant 1 mm displacement sinusoidal input Air suspension with dampers - both axles excited in phase

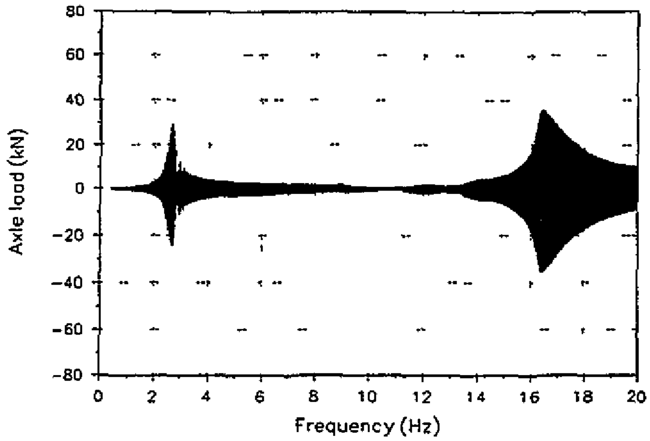

Fig 4 Constant 1 mm displacement sinusoidal input Rubber suspension - both axles excited in phase

The in-phase constant amplitude sinusoidal sweep excitation test has proven to be most effective at distinguishing suspension response at both the sprung mass and unsprung mass frequencies This technique also has the capability of proving damper effectiveness and can be used to assess the condition of the suspension and dampers at intervals during the working life of the suspension The 1 mm constant amplitude stroke requires minimal energy input to the system and can be achieved through the use of hydraulic shakers or a special purpose mechanical system

OUT-OF-PHASE SINUSOIDAL FREQUENCY SWEEP

The 180 degree out-of-phase sinusoidal excitation was conducted for a range of constant amplitudes from DC to 20 Hz The continuous frequency sweep was conducted at 5 Hz per minute The various constant single amplitude displacements used were, 1, 2, 3, 4, 6 and 8 mm As with the in-phase excitation, displacements of 1 mm produced the best results As expected, the out-of phase excitation failed to influence the sprung mass which makes this method unsuitable for suspension assessment This method did however, excite the coupled axles of the walking beam in pitch

The out-of-phase sinusoidal frequency sweep is not suitable as a test for suspension road friendliness however it does hold promise as a method for assessing the coupled axle pitch dynamics of walking beam suspensions

DIVINE AND VIRTUAL ROAD PROFILES

The primary goal of this research effort is to arrive at a recommended test procedure for suspension assessment One method is to use the road simulator to replicate waveforms common to roadways Three "actual" road sections representing roads of good, average, and poor unevenness were selected and the vertical profiles of the wheel paths were measured The International Roughness Index (IRI) for the sections was calculated and is shown in Table 4

Table 4 International Roughness Index For DIVINE road profiles

Road Surface Unevenness	International Roughness Index
Good	0 97
Average	2 23
Poor	4 46

Three road sections were selected and profiled to serve as a standard road set for the DIVINE Program These profiles were used to drive the simulator to assess the response of the three suspensions at different speeds The profiles were created by measuring the vertical profile of left and right wheel paths To eliminate roll input to the vehicle while on the shaker, the left wheel path profile was used to drive the left and right actuators Road simulator tests were conducted for the three profiles using three different suspensions fitted to the standard test trailer The DLC's were calculated and plotted to permit comparison

A second set of similar experiments were conducted using a "virtual" road profile representing generic good, average and poor roads The character of the virtual road profile was defined in terms of the slope of the power spectral density (PSD) A slope of -2 on a displacement spectral density (m^3/cycle) versus wave-number (cycles/m) was found to represent a strong first order approximation of the actual road profiles and also produced constant power as a function of frequency The magnitude of the virtual road profile was adjusted to approximate the good, average, and poor unevenness of the DIVINE road profiles Evaluated at the wave-number of $1/2\pi$, the magnitudes used are listed in Table 5

Table 5 Magnitude of the virtual road profiles and approximate IRI equivalency

Road Surface Unevenness	International Roughness Index	Displacement Spectral Density (m^3/cycle)
Good	0 97	2 7 x 10^{7}
Average	2 23	4 5 x 10^{6}
Poor	4 46	2 7 x 10^{5}

Exciting suspensions using the DIVINE or VIRTUAL road profiles provide a comprehensive means for suspension assessment The ranking of suspension road-friendliness was found to be consistent with what actually happens on the roads The suspension dynamic load coefficient (DLC) ranking resulting from the DIVINE road profile input is very similar to that resulting from the VIRTUAL road profile Of the two inputs, the VIRTUAL road profile is the better choice for a standard test road profile input because it can be generated and referenced independently of measured road profiles However, both of these tests can only be performed on a full scale shaker which is limiting Because of the high capital costs of shaker systems, this test will not be a practical means of assessing suspension road friendliness compliance at intervals during the life of the suspension

The results from road simulator testing compare favorably with road tests The ranking of suspension road-friendliness is consistent in both cases Road simulator testing does however produce higher dynamic axle loads This increase is largely attributed to tractor/trailer interaction

SIMULATED DROP TESTS

The simulated drop test was structured to replicate the compliance test outlined in the EC drop test Directive 92/7/EEC, which defines the equivalency of non-air suspensions to air suspensions Additional tests were conducted to examine the sensitivity of the damping parameter to primary variables including drop height and drop sequence The shaker was used to achieve the axle drop under the following conditions

- simultaneous axle drop (both axles are dropped at the same time),
- single axle drop (only one axle is dropped in a given test),
- sequential axle drop (each axle is dropped in sequence at a simulated vehicle speed of 5 km/h),

- drop height variations (40, 60, 80, 100 and 120 mm)

Directive 92/7/EEC requires that when a vehicle is subjected to an 80 mm drop, the sprung mass frequency must not be greater than 2 0 Hz and that the damping ratio $D_{1\,2}$ must be greater than 20% of critical The damping ratio can be resolved by measuring the successive peaks of the vehicle wheel load or body displacement responses immediately after the event and then applying the values to the standard damping ratio equation below

$$D_{1\,2} = \frac{1}{2\pi} \bullet \ln\left(\frac{A_1}{A_2}\right)$$

Simultaneous Axle Drop
Dropping the axles simultaneously through a vertical distance of 80 mm is considered to be a valid test for compliance with EC Directive 97/7/EEC In general, the experiments found that damping ratio decreased with increased drop height The damping ratio of the air suspension increases as successive response peaks are used to calculate damping Considering the suspensions examined, the drop test did provide a means for determining the damping ratio, although there are considerable variations in the results

The simultaneous axle drop tests provide a clear separation between mechanical and air suspensions with regard to sprung mass frequency and damping This test also clearly indicates damper performance The results reported here are from controlled tests on a pivoted test bed There was no interaction from adjacent suspensions A recent study (11) examined the simultaneous axle drop tests on articulated vehicles using removable ramps and found similar results to those reported here

Single Axle Drop
The single axle drop tests were performed on tandem axle suspensions The air suspension produced response curves that were not readily distinguishable

Sequential Axle Drop
The sequential axle drop simulated a vehicle traversing the standard ramp specified in EC drop test Directive 92/7/EEC at a speed of 5 km/h Tire enveloping effect associated with the tire leaving the edge of the ramp was not considered

The sequential axle drop tests did not produce results that were as clear and consistent as the simultaneous drop test The damping ratios determined from the sequential tests, in most cases, did not agree with those determined from the simultaneous drop tests They were either higher or lower in value There was excellent agreement in the sprung mass frequency determined by either test method This method is not considered suitable for suspension road-friendliness assessment

CONCLUSIONS

1 Quasi-static load equalization is a very important suspension performance attribute because suspensions that equalize axle loads poorly impose consistently higher road distress than suspensions that equalize them well

2 The in-phase 1 mm constant amplitude sinusoidal sweep excitation test has proven to be effective at distinguishing suspension response at both the sprung mass and unsprung mass frequencies This technique also has the capability of proving damper effectiveness and can be used to assess the condition of the dampers at intervals during the working life of the suspension

3 The results from road simulator testing compare favorably with road tests and the ranking of suspension road-friendliness is consistent in both cases Road simulator testing on the trailer alone does produce higher dynamic axle loads because of the lack of tractor/trailer interaction The VIRTUAL road profile is the better choice for standard road profile input because it can be generated and referenced independently of measured road profiles

4 The simultaneous axle drop tests provide a clear separation between mechanical and air suspensions with regard to sprung mass frequency and damping This test also clearly indicates damper performance As with the other methods, the interaction between the tractor and trailer must be eliminated to accurately assess the performance of a particular suspension

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Roaduser Research specializes in the applications of technical knowledge and advanced engineering methods to the heavy truck and trailer industry for the purpose of improved road transport efficiency and safety

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