Spatial Correlation Of Dynamic Wheel Loads

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ABSTRACT

The significance of the problem of pavement wear caused by heavy vehicle dynamic wheel loads depends to a great extent on the spatial correlation properties of wheel loads. An experimental programme was carried out by the National Research Council of Canada (NRC) to investigate the fundamental properties of wheel load spatial correlation, and to measure spatial correlation between wheel loads from a group of seven different tractor-trailer configurations. The analysis performed to date focuses on the principal characteristics of spatial repeatability as a function of vehicle design and operating conditions, and indicates that dynamic wheel loads applied by different types of heavy vehicles are moderately correlated in the spatial domain.

INTRODUCTION

Concerns about growing government budgetary deficits, awareness of the economic advantages of a well maintained road infrastructure, and the desire to equitably distribute the cost of road use among road users are some of the important reasons for the need to better understand the problem of pavement wear caused by heavy vehicles.

Vertical forces generated at the pavement/tire interface of heavy vehicles are the principal source of vehicle-generated pavement wear. As a result of road roughness and vehicle speed these vertical forces, or wheel loads, oscillate about a mean value. A portion of the pavement wear caused by wheel loads is attributable to the mean value of wheel loads, known as static wheel loads, while the remainder is attributable to the dynamic component of wheel loads, known as dynamic wheel loads.

Results obtained in numerous experimental studies* have shown that the magnitude of dynamic wheel loads varies significantly with the basic design, and the performance of key components, of heavy vehicle suspension systems.

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* A comprehensive list of articles on dynamic wheel loading experiments is compiled in reference [1].

Thus, potential reductions in road maintenance costs, or improvements in the level of serviceability of the road infrastructure, can result from an increase in the use of so-called *road-friendly* suspension systems, suspensions that produce low dynamic wheel loads, and have good static wheel load equalization properties during braking and in constant speed operation.

The reduction in pavement wear resulting from an increase in use of road-friendly suspensions depends on the current level of *spatial repeatability* of dynamic wheel loads, and on the tendency of spatial repeatability to change as a result of the increase in use of road-friendly suspensions [2].

The objectives of the spatial correlation experiments were to investigate the principal characteristics of wheel load spatial correlation as a function of vehicle design and vehicle operating conditions, and determine if wheel loads applied by different types of vehicles are strongly, moderately, or weakly correlated in the spatial domain.

SPATIAL REPEATABILITY

Two wheel load signals are said to be spatially repeatable, or strongly correlated in the spatial domain, when their peaks and lows generally recur in the same locations along the road. Pavements are expected to wear significantly faster if wheel loads applied by different heavy vehicles are generally strongly correlated in the spatial domain, than if they are not.

The importance of the issue of spatial repeatability can be illustrated by applying the *fourth power law*, and its derivatives, to experimental results obtained with road-friendly and road-unfriendly suspensions. A partial summary of experimental results obtained by NRC is shown in Table 1, where the coefficient of variation of wheel loads (or, Dynamic Load Coefficient - DLC) are listed as a function of road roughness for a tractor air-spring suspension and a tractor walking-beam steel-spring suspension. Road roughness is expressed in terms of the International Roughness Index (IRI).

Table 1. DLCs for tractor suspensions.

Road Roughness (IRI)	Air-Spring (DLC)	Steel-Spring Walking-Beam (DLC)
1.1 (smooth)	.03	.09
3.5 (average)	.08	.26
4.7 (rough)	.11	.37

If dynamic wheel loads are weakly correlated in the spatial domain, then pavement wear caused by a dynamic wheel load should be evaluated with respect to the average wear caused by the wheel load. On the other hand, if dynamic wheel loads are strongly correlated in the spatial domain, then the pavement wear caused by a dynamic wheel load should be evaluated with respect to localized wear caused by the peak values of the wheel load. The percentage increase in pavement wear resulting from using a tractor steel-spring walking-beam suspension instead of a tractor air-spring suspension are shown in Table 2 as a function of road roughness, for the case where wheel loads are weakly correlated (Column 2) and for the case where wheel loads are strongly correlated (Column 3). The values in Columns 2 and 3 correspond to the DLCs shown in Table 1, and are based on the assumption that the fourth power law holds. The values in Column 2 are derived from Eisenman's formula which expresses pavement wear as a function of DLC [3], while the values in Column 3 are based on pavement wear caused by the 95th percentile of the wheel loads' probability distributions [4].

The results shown in Table 2 illustrate the importance of the issue of spatial repeatability of dynamic wheel loads. Moreover, given that it is more important to find ways to preserve smooth and moderately smooth roads, than it is to preserve rough roads, the results in the first two rows are of greater importance. That is, the comparison should be limited to potential increases in pavement wear of 43% and 150% for strongly correlated wheel loads versus increases of 4% and 37% for weakly correlated wheel loads.

Table 2. Percentage increase in pavement wear resulting from the use of a steel-spring walking-beam suspension versus an air-spring suspension.

Road Roughness (IRI)	Percentage Increase in Pavement Wear	
	Weakly Correlated Wheel Loads	Strongly Correlated Wheel Loads
1.1 (smooth)	4%	43%
3.5 (average)	37%	150%
4.7 (rough)	75%	245%

EXPERIMENTAL PROGRAMME

The spatial repeatability tests were conducted using NRC's research tractor-trailer (Figure 1). The vehicle consists of a three-axle tractor and a three-axle trailer including a lift axle located at the centre of the trailer.

INSTRUMENTATION
All wheels, with the exception of the steer axle wheels, were instrumented to measure dynamic wheel loads. The wheel load instrumentation was thoroughly calibrated on NRC's shaker facility [5].

Considerable effort was devoted towards the development of a vehicle odometer whose "precision" was compatible with the wheel load instrumentation's ability to measure dynamic wheel loads. NRC's wheel load instrumentation is capable of measuring dynamic wheel loads over a typical wheel load frequency spectrum of 0 to 15 Hz without any appreciable error in phase. A decision was made, therefore, to develop an odometer capable of locating the longitudinal position of a hypothetical 15 Hz dynamic wheel load with a repeatability of ± 5 deg from where the load actually occurred. Note that given the requirements of the spatial repeatability experiments, the development of the odometer focused mainly on the repeatability of the measurements as opposed to their precision.
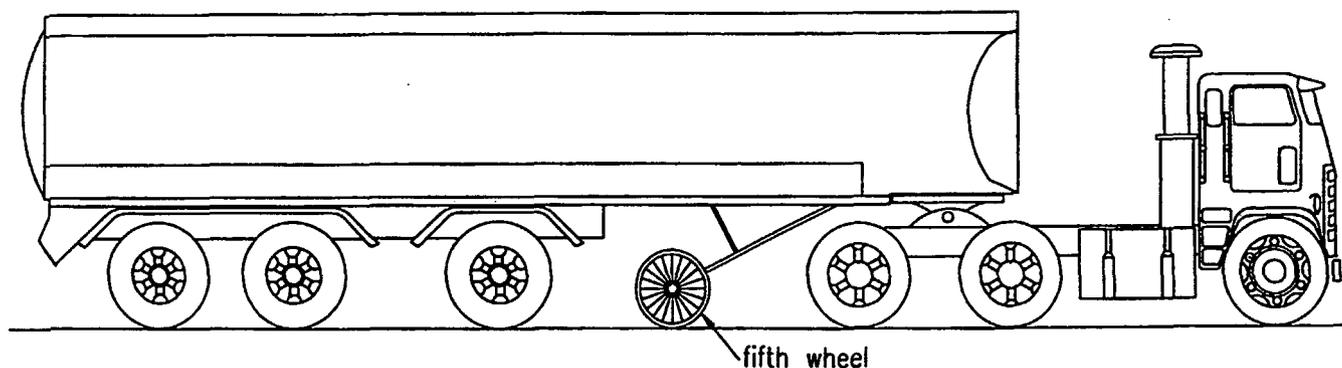

Figure 1. NRC research tractor-trailer shown with fifth wheel, one of three main components that comprises the high precision odometer developed by NRC for the spatial repeatability experiments.

For a speed of 75 km/h (the lowest test speed considered during the tests), a repeatability of $\pm$ 5 deg for a 15 Hz wheel load signal translates into an odometer repeatability of $\pm$ .02 m. Given that no commercially available odometer could satisfy this requirement, the odometer was developed in-house. Details of the odometer have been reported by Zwarts et al [7].

TEST VEHICLE CONFIGURATIONS

Seven tractor-trailer configurations were tested using NRC's specially designed research tractor-trailer [6]. The tractor-trailers were configured from two different tractor suspensions, two different trailer suspensions, two different payloads, and with two different lift axle positions, raised or lowered (Table 3). Steel-spring walking-beam and air-spring suspensions were used on the tractor, whereas rubber-spring walking-beam and air-spring suspensions were used on the trailer. These suspension systems were selected because they provided extremes in dynamic wheel loading performance. The lift axle was lowered for the heavy payload and raised for the light payload. The trailer consisted of a four-compartment tank. The front and rear compartments were filled to capacity for the heavy load (30,000 l), whereas the two middle compartments were filled to capacity for the light payload (18,000 l).

The tractor tandem inter-axle spacing was fixed at 1.52 m. The trailer tandem inter-axle spacings were 1.38 and 1.82 m for the rubber-spring and air-spring suspensions, respectively. The distance between the centre of the tandem axle groups were 10.76 m for configurations with the trailer rubber-spring suspension, and 10.36 m for configurations with the trailer air-spring suspension. These distances led to minimum and maximum distances between trailer and tractor tandem axles of 8.69 and 12.21 m, respectively.

The spatial repeatability tests were conducted on three road sections. They consisted of a rough section, a section of average roughness, and a smooth section. Road profiles were measured for each section using a Dipstick. The corresponding IRIs are shown in Table 4 with the respective lengths of the road sections.

Table 4. Description of road sections.

Site #	Length (m)	Road Roughness (IRI)	Nominal Rating
1	750	4.7	Rough
2	750	3.5	Average
3	750	1.1	Smooth

The vehicles were tested at 3 different speeds, namely, 75, 85, and 95 km/h. Tests for each combination of vehicle speed, site, and vehicle configuration were conducted 3 times. A total of 279 wheel load space-histories were recorded for each of the six wheel paths (3 sites x 2 wheel paths/site).

EXPERIMENTAL RESULTS

Wheel load spatial correlation was evaluated in terms of the correlation coefficient between two wheel load "space-histories" in a given wheel path. Spatial correlation coefficients as high as .98 were obtained for repeat runs, while values hovering about zero were obtained in other situations.

REPEAT RUNS

Correlation coefficients considered in this sub-section correspond to those for specific wheels in repeat runs. For example, they include correlation coefficients between Wheel Load 6 during Run 1 and Wheel Load 6 during Run 2, where Runs 1 and 2 are carried out with the same vehicle configuration, driven at the same speed, over the same road section. See Table 5 for wheel numbering convention. Partial results are shown in Figure 2. They reveal that spatial correlation increases with road roughness for air-spring suspensions, but decreases marginally with road roughness for walking-beam suspensions.

Power spectral density (PSD) curves corresponding to the air-spring suspensions on the smooth section reveal significant wheel load components at frequencies of 6.4, 7.3, or 8.1 Hz. These load components are caused by

Table 3. Tractor-trailer configurations used in spatial repeatability experiments.

Configuration #	Tractor Suspensions	Trailer Suspensions	Payload
1	Air-spring	Rubber-spring walking-beam	Heavy payload, lift axle down
2	Air-spring	Rubber-spring walking-beam	Light payload, lift axle up
3	Air-spring	Air-spring	Light payload, lift axle up
4	Air-spring	Air-spring	Heavy payload, lift axle down
5	Steel-spring walking-beam	Air-spring	Heavy payload, lift axle down
6	Steel-spring walking-beam	Air-spring	Light payload, lift axle up
7	Steel-spring walking-beam	Rubber-spring walking-beam	Light payload, lift axle up

Table 5. Wheel numbering convention.

Axle	Driver side	Passenger side
Tractor lead drive	Wheel 1	Wheel 2
Tractor trailing drive	Wheel 3	Wheel 4
Trailer lead tandem	Wheel 5	Wheel 6
Trailer trailing tandem	Wheel 7	Wheel 8
Lift	Wheel 9	Wheel 10

wheel imbalance, and correspond to speeds of 75, 85, and 95 km/h, respectively. The magnitude of wheel load components originating from wheel imbalance is independent of road roughness. And so, as road roughness decreases, these load components which are not repeatable in space gain significance compared with load components originating from sprung-mass and unsprung-mass motions which are generally repeatable in space. This provides a possible explanation why wheel load spatial correlation for the air-spring suspensions is lower on the smooth section than on the average and rough sections.

PSD curves also show that wheel imbalance is more prominent for the trailing drive-axle, than for the lead drive-axle. Again, wheel imbalance provides a possible explanation why wheel load spatial correlation is lower for the trailing drive-axle than for the lead drive-axle (Figure 2).

PSD curves for the walking-beam suspensions reveal that, even on the smooth section, load components originating from wheel imbalance are small compared with load components originating from sprung-mass and unsprung-mass motions. This PSD result is in agreement with results shown in Figure 2 – spatial correlation coefficients are not lower on the smooth section than on the rougher sections for the walking-beam suspensions.

If wheel imbalance is the only cause for the lower level of spatial correlation experienced on smooth roads by the air-spring suspensions, then this lower level of spatial correlation does not, by itself, make the air-spring suspensions road-friendlier than the walking-beam suspensions. The additional pavement wear caused by wheel imbalance is expected to be identical for both types of suspensions.

No solid argument has been found to explain the marginal decrease in spatial correlation experienced by the walking-beam suspensions on the rough section.

EFFECT OF SPEED

Correlation coefficients considered in this sub-section correspond to those for specific wheels in runs conducted at different vehicle speeds. For example, they include correlation coefficients between Wheel Load 4 during Run 1 and Wheel Load 4 during Run 2, where Run 1 is carried out at 75 km/h, and Run 2 is carried out at 75, 85 or 95 km/h.
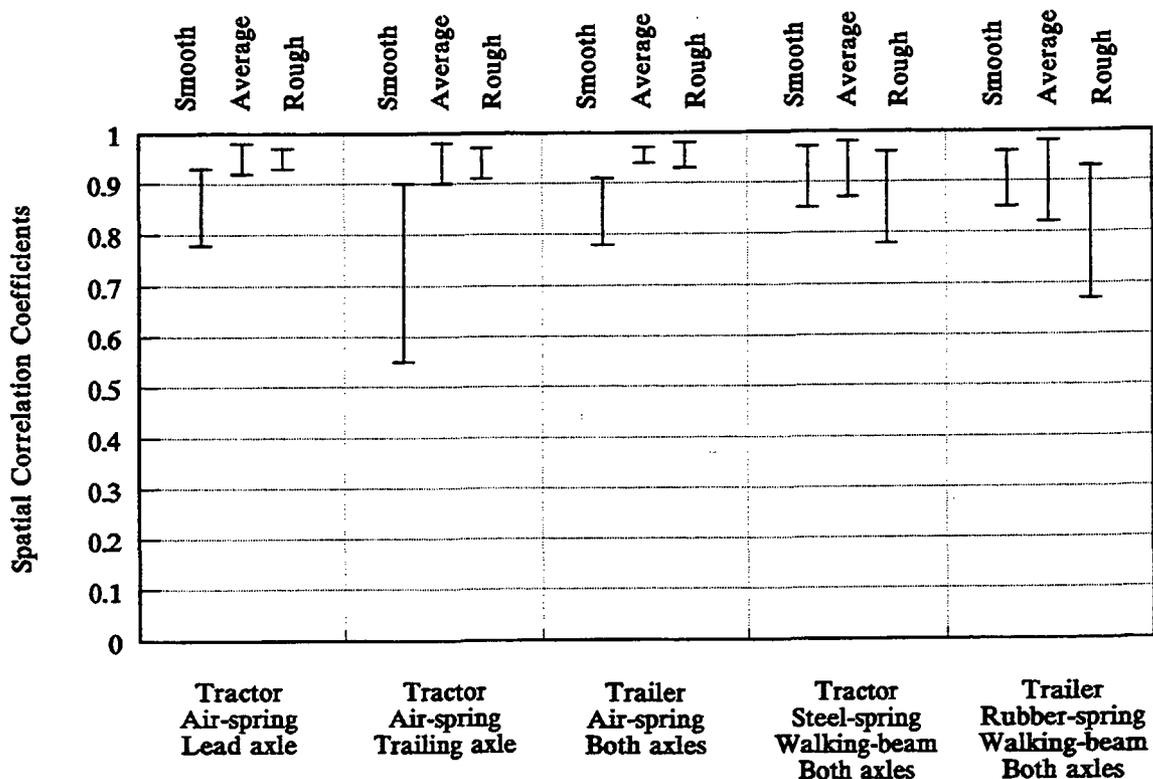

Figure 2. Correlation coefficients between specific wheels in repeat runs.

Typical results are shown in Figure 3. They reveal that spatial correlation is highly sensitive to vehicle speed for walking-beam suspensions. For example, a 10 km/h change in vehicle speed can cause spatial correlation coefficients to drop from .97 to .30. On the other hand, spatial correlation for air-spring suspensions is significantly less sensitive to changes in vehicle speed. A 10 km/h change in speed causes the spatial correlation coefficients to drop from .95 to .80.
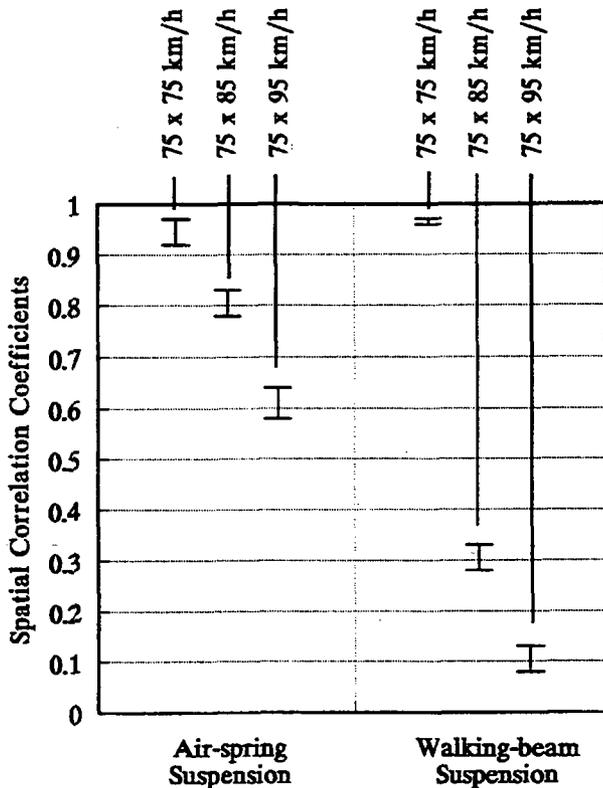
different speeds. For example the correlation coefficient between the two wheel loads whose PSDs are shown in Figures 4 and 5 may be zero when travelling at the same speed and rise above .5 when travelling at different speeds.
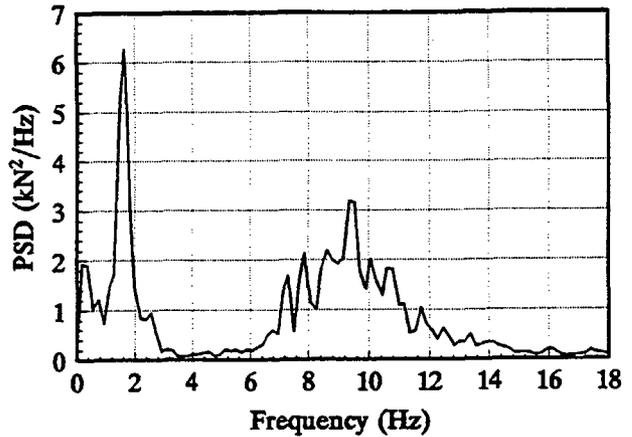

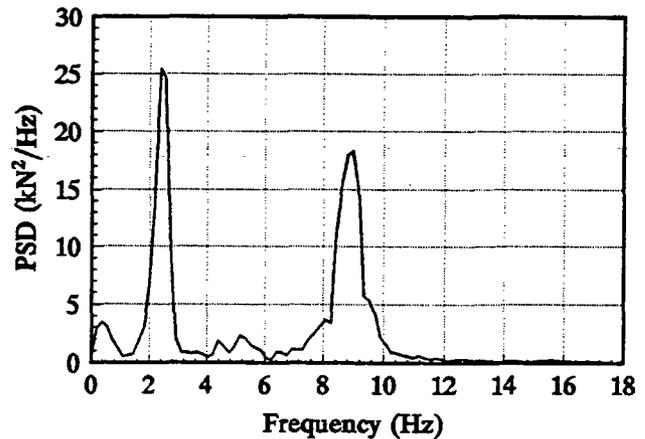Figure 4. Typical PSD for air-spring suspension.

Figure 3. Correlation coefficients for specific wheels in runs conducted at different speeds.

Figure 5. Typical PSD for walking-beam suspension.

The main reason why spatial correlation is more sensitive to vehicle speed for walking-beam suspensions than for air-spring suspensions, is that wheel loads for walking-beam suspensions are concentrated in narrow frequency bans, whereas those for air-spring suspensions are spread over much wider bans (Figures 4 and 5). The effect of speed on narrow frequency bans can be illustrated by considering the frequency ban for the unsprung-mass of the walking-beam suspension, which ranges approximately between 8.5 and 9.5 Hz (Figure 5). At 75 km/h, the unsprung-mass produces wheel load space-histories having wavelengths between 2.19 and 2.45 m, whereas at 85 km/h, wavelengths range between 2.49 and 2.78 m. Thus, if wheel load components below 8.5 Hz were filtered, the resultant spatial correlation coefficients would be equal to 1 for 75 x 75 km/h runs and zero for 75 x 85 km/h runs.

An additional consequence of the frequency-versus-speed phenomenon, is that two vehicles with significantly different wheel load PSDs may exhibit very low levels of spatial correlation when operated at the same speed, but relatively high levels of spatial correlation when operated at

EFFECT OF SUSPENSION TYPE

Two types of correlation coefficients are considered in this sub-section. Those that correspond to specific wheels in repeat runs, and those that correspond to specific wheels in runs carried out with different tractor suspensions. More precisely, the latter include spatial correlation coefficients between Wheel Load n of the tractor during Run 1 and Wheel Load n of the tractor during Run 2, where Runs 1 and 2 are carried out at the same speed, with the same payload, but with a different tractor suspensions.

The results shown in Figure 6 correspond to vehicle Configurations 3 and 6 (Table 3). The only difference between the two vehicle configurations is that Configuration 3 has a tractor air-spring suspension, while Configuration 6 has a tractor steel-spring walking-beam suspension. The data shown in the first and second "columns" corresponds to repeat runs for Configurations 3 and 6, respectively, while the data in the third column corresponds to correlation coefficients between runs with Configuration 3 and runs with Configuration 6.

Comparison of results from Figures 3 and 6 reveals that, for a walking-beam suspension, changing the vehicle speed by 10 km/h can reduce spatial correlation by a greater amount than that caused by replacing the walking-beam suspension with an air-spring suspension.
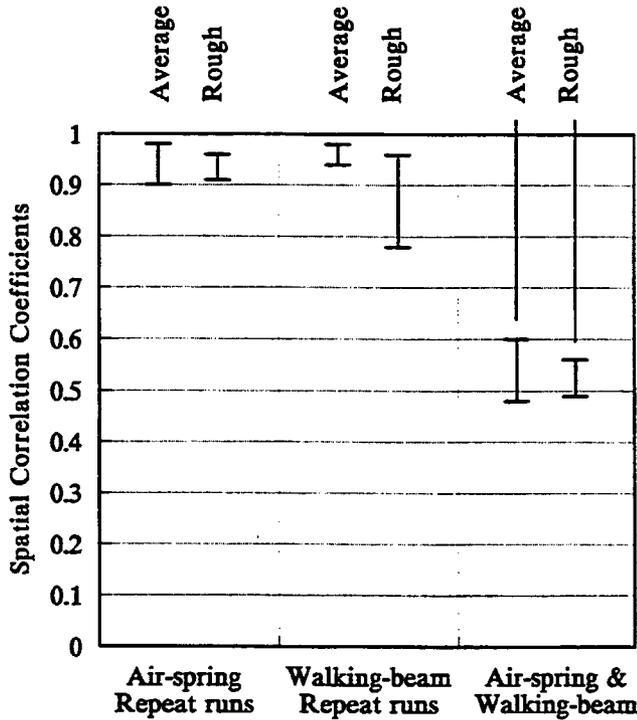

Figure 6. Correlation coefficients between specific wheels from similar and different tractor suspensions.

SPATIAL CORRELATION WITHIN TANDEM AXLE GROUPS

Correlation coefficients considered in this sub-section correspond to those between the lead and trailing axles for a specific tandem axle group within a single run. Typical results are shown in Figure 7 for an air-spring and a walking-beam suspension at the test speeds of 75, 85, and 95 km/h.

The spatial correlation coefficients are marginally sensitive to vehicle speed for the air-spring suspensions, but are significantly sensitive to vehicle speed for walking-beam suspensions. The principal reason for this is that the lead and trailing axle motions are independent from one another for the air-spring suspensions, but are dependent on one another for the walking-beam suspensions.

The wheel load components associated with pitch motion of the walking beam, hereafter referred to as pitch loads, are of significant magnitude, and affect spatial correlation in the following manner. The lead and trailing axle pitch loads are out-of-phase by 180 degrees in the time-domain. Therefore, if a peak pitch load for the lead axle occurs at point X, then peak pitch loads for the trailing axle occur at points of $X - L + \lambda/2 + n\lambda$, where L is the tandem inter-axle spacing, λ is the wavelength of one load cycle, and $n = \ldots -1, 0, 1, 2,\ldots$ Lead axle and trailing

axle peak pitch loads are separated by a distance equal to the minimum value of set $D_n = |L - \lambda/2 - n\lambda|$.

If pitch loads are the only wheel load components involved, then spatial correlation coefficients will take on a value of 1 when $D_{n,min} = 0$, a value of 0 when $D_{n,min} = .25 \cdot \lambda$, and a value of -1 when $D_{n,min} = .5 \cdot \lambda$. The walking-beam suspension whose results are shown in Figure 7 has a walking-beam pitch frequency of 9 Hz, and an inter-axle spacing of 1.52 m. This leads to $D_{n,min}$ values of .16·λ, .08·λ .02·λ, for speeds of 75, 85 and 95 km/h, respectively, and implies an increase in spatial correlation for the increase in vehicle speed. These anticipated results are in agreement with actual results shown in Figure 7.
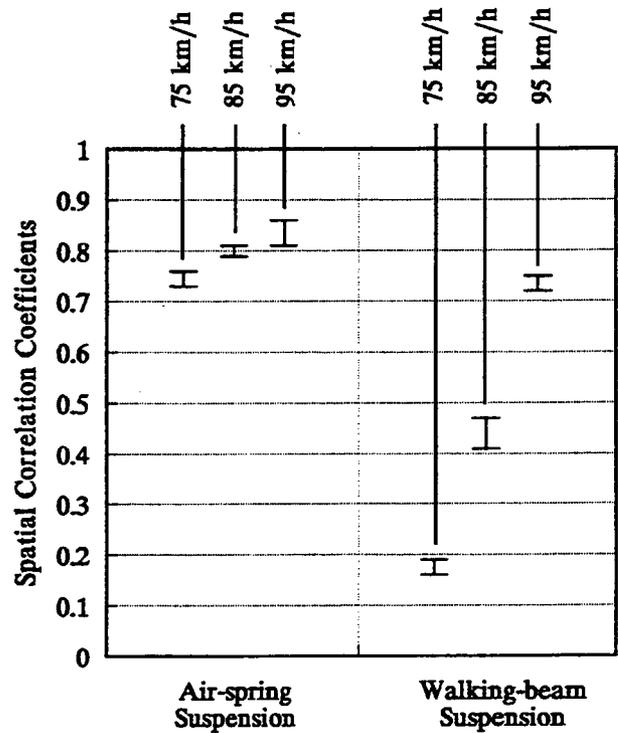

Figure 7. Correlation coefficients between wheels of lead and trailing axles of tandem axle groups.

A similar analysis, based on sprung-mass wheel load components, shows that for the sprung-mass resonance frequencies of the tractor-trailers involved in the experiments and for the tandem inter-axle spacing of 1.52 m, increasing the speed from 75 to 95 km/h will increase the spatial correlation between the lead and trailing axles of the tandem axle groups. Hence, this provides a second explanation for the large increase in spatial repeatability observed for the walking-beam suspension, and the principal explanation for the moderate increase in spatial repeatability observed for the air-spring suspension.

SPATIAL CORRELATION BETWEEN TRACTOR AND TRAILER SUSPENSIONS

Correlation coefficients considered in this sub-section correspond to those between the tractor wheel loads and trailer wheel loads during repeat runs. Summary results are

shown in Figure 8 for the seven tractor-trailer configurations considered in the study.

The two vehicle configurations with tractor and trailer air-spring suspensions produced spatial correlation coefficients that are slightly higher than those produced by the remaining five vehicle configurations. This is particularly true on the average and rough road sections. The reasons for the higher correlation have not yet been fully investigated, but probable causes are described below.

The discussion that follows is based on two general points concerning the analysis of wheel load spatial correlation. First, the level of spatial correlation between any two wheel loads depends, not only, on similarity between spatial-domain power spectra, but also on similarity between spatial-domain phase spectra. For example, two wheel load space-histories predominated by components of comparable wavelengths will only be strongly correlated if the two space-histories have comparable phase. Secondly, spatial repeatability can be analyzed more thoroughly by separating the effects of wheel load components corresponding to sprung-mass motions from those corresponding to unsprung-mass motions. It is worth noting, for example, that increasing the spatial correlation between the load components for unsprung-mass motions will increase the overall spatial correlation.

Spatial correlation between sprung-mass wheel load components are governed by the tractor-trailer's sprung-mass resonance frequencies, the vehicle speed, the three mode shapes of the sprung mass, and the two main inter-axle spacings (i.e., steer axle to centre of tandem drive axles, and centre of tandem drive axles to centre of tandem trailer axles). No attempt has been made to determine if sprung-mass wheel load components are more correlated for the vehicle configurations with two air-spring suspensions, than for the other five configurations. And, there are no reasons to believe that this would be the case.

Spatial correlation between unsprung-mass wheel load components are governed by the suspensions' unsprung-mass resonance frequencies, the vehicle speed, and, in the case of the walking-beam suspensions, by two mode shapes and the tandem inter-axle spacing. No attempt has been made to determine if unsprung-mass wheel load components are more correlated for the vehicle configurations with two air-spring suspensions, than for the other five configurations. However, there are two reasons to believe that this is generally the case.

The first reason is that the unsprung-mass power spectra is generally spread over a significantly wider frequency ban for air-spring suspensions than for walking-beam suspensions. This increases the possibility of overlap of power
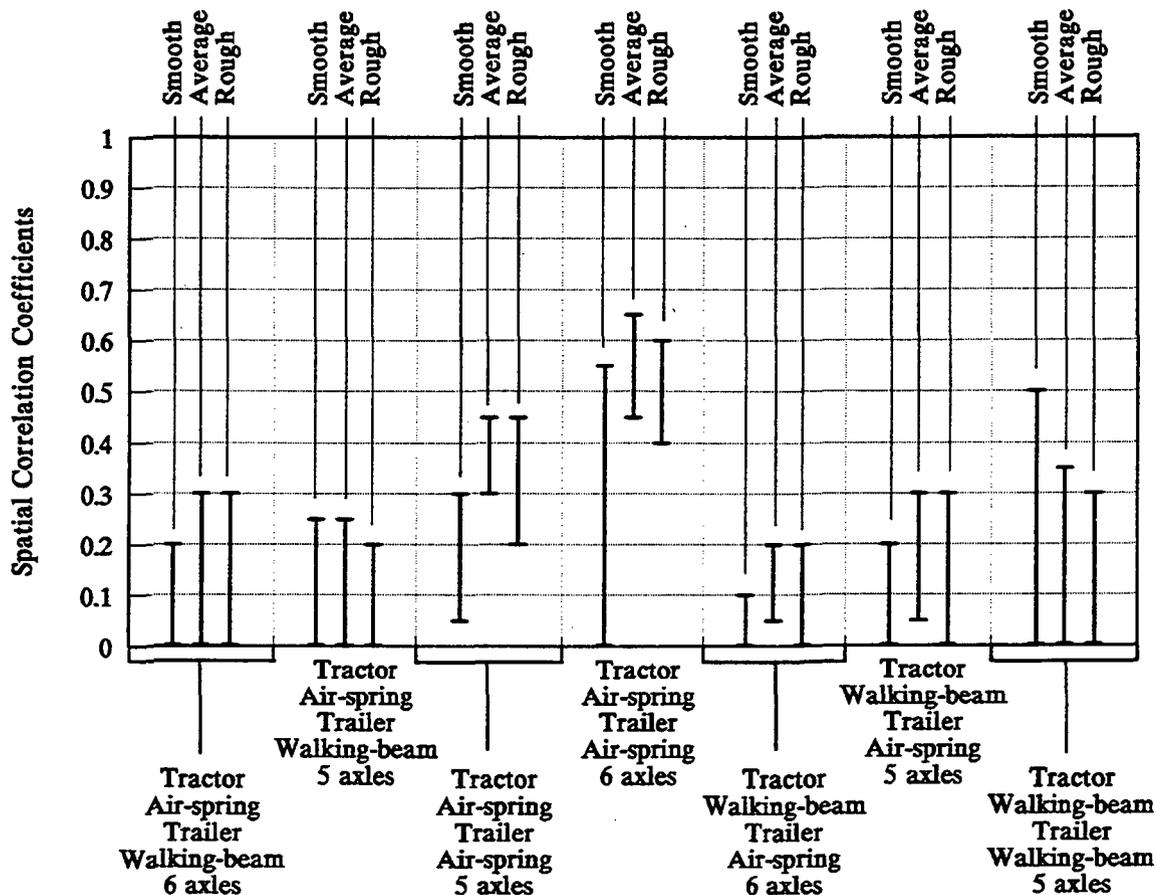

Figure 8. Correlation coefficients between tractor wheel loads and trailer wheel loads in repeat runs.

spectra. The PSD curves in Figures 9 and 10 prove the point. The peak values of the unsprung-mass spectra for the two air-spring suspensions are approximately 2 Hz apart (viz., 9.5 and 11.5 Hz), while the peak values for the unsprung-mass spectra for the two walking-beam suspensions are also approximately 2 Hz apart (viz., 9 and 11 Hz). Yet, the spectra overlap for the unsprung-mass load components is significantly greater for the air-spring suspension than for the walking-beam suspension.

The second reason why unsprung-mass wheel load components are potentially more correlated for vehicles with the two air-spring suspensions is that air-spring suspensions are independent while walking-beam suspensions are not. Because axle motions in air-spring suspensions are characterized by a single mode of vibration (the bounce mode), unsprung-mass wheel load components which overlap on the spatial-domain power spectra are expected to have identical phase spectra. This is not expected to be the case for walking-beam suspensions which are characterized by two modes of vibration, a bounce mode and a pitch mode.

Although the assertions presented above are plausible, they need to be substantiated with further analysis of the experimental data.
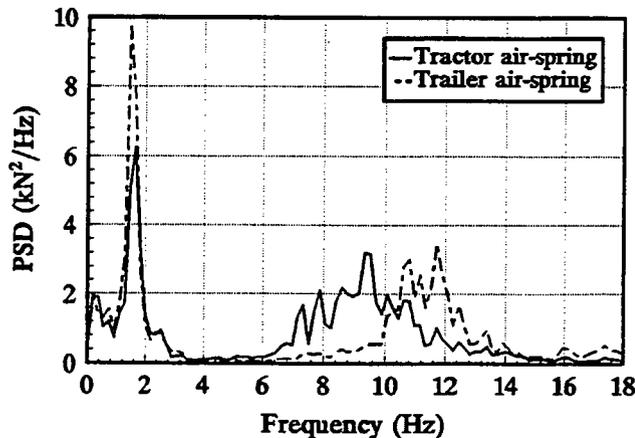

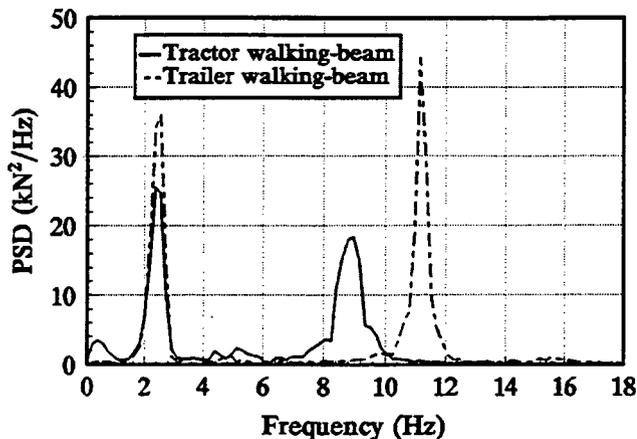Figure 9. Typical PSDs for tractor and trailer air-spring suspensions.

Figure 10. Typical PSDs for tractor and trailer walking-beam suspensions.

EFFECT OF SPEED, SUSPENSION TYPE, PAYLOAD, AXLE CONFIGURATION, AND AXLE LOCATION

Correlation coefficients considered in this sub-section correspond to those between any wheel on a given tractor-trailer configuration and any wheel on a different tractor-trailer configuration.

The statistical analysis is not complete, but results compiled to date show that, for the seven tractor-trailer configurations considered in the study, wheel loads are moderately correlated in the spatial domain. Spatial correlation coefficients range between -.2 and .9, but tend to be concentrated between values of .2 and .5.

Preliminary statistical results indicate that spatial correlation is higher for subsets of vehicle configurations where a particular suspension type is kept constant. For example, spatial correlation coefficients between the four tractor-trailer configurations with the tractor air-spring suspensions tend to be concentrated in a range that exceeds the range of .2 to .5 obtained for the seven configurations.

Preliminary statistical results also indicate that spatial correlation may, on average, be slightly lower on smooth roads, although opposite results were found in numerous specific cases. Hence, no definite conclusion can be drawn until the completion of the statistical analysis.

SUMMARY

Results from the experiments and analysis can be summarized as follows.

1. Spatial correlation coefficients for specific wheels in repeat runs are generally above .80 and can reach values as high as .98.

2. Spatial correlation for repeat runs on the smooth road section was found to be lower for air-spring suspensions than walking-beam suspensions. However, this result may be due to wheel imbalance.

3. Spatial repeatability for walking-beam suspensions is highly dependent on speed. Spatial correlation coefficients can drop from .97 to .30 as a result of a mere 10 km/h change in vehicle speed. Spatial correlation for air-spring suspensions is significantly less affected by variations in vehicle speed.

4. Two vehicles with significantly different wheel load PSDs may exhibit very low levels of spatial correlation when operated at the same speed, but relatively high levels of spatial correlation when operated at different speeds.

5. Wheel load spatial correlation between the lead and trailing axles of tandem axle groups is higher for air-spring suspensions than for walking-beam suspensions.

6. Spatial correlation coefficients between tractor wheel loads and trailer wheel loads in repeat runs were generally quite low, and rarely above .5. These correlation coefficients were slightly higher for the two vehicle configurations with tractor and trailer air-spring suspensions. This was particularly true on the average and rough road sections.

7. Results compiled to date show that, for the seven tractor-trailer configurations considered in the study, wheel loads are moderately correlated in the spatial domain. Spatial correlation coefficients ranged between -.2 and .9, but were concentrated between values of .2 and .5.

8. Preliminary results indicate that spatial correlation may be higher when a particular suspension type is kept constant. Preliminary results also indicate that spatial correlation may, on average, be slightly lower on smooth roads than on rougher roads. These two findings are not conclusive and need to be substantiated by further statistical analysis of the experimental data.

CONCLUSIONS

The issue of wheel load spatial repeatability is surrounded by seven main questions. Namely.

1) What are the principal characteristics of spatial repeatability as a function of vehicle design and operating conditions?
2) Are wheel loads applied by different types of heavy vehicles strongly, moderately, or weakly correlated in the spatial domain?
3) What is the relationship between pavement wear caused by wheel loads, and the DLC, the static wheel load and spatial correlation?
4) Will spatial repeatability increase significantly as a result of wide spread use of road-friendly suspensions?
5) Are certain suspension types inherently susceptible to produce high levels of spatial repeatability?
6) Is spatial repeatability expected to increase significantly due to potential convergence towards optimum weights-and-dimensions layouts?
7) Can spatial repeatability, and ultimately pavement wear, be reduced by using road-friendly vehicles?

The analysis performed to date has focused on answers to the first two questions.

Some of the principal characteristics of spatial repeatability as a function of vehicle design and operating conditions have been established and are summarized in points 1 to 6 of the previous section. An important relationship that has not yet been established, is the relationship between spatial repeatability and road roughness. This will require further analysis of the experimental data.

The spatial correlation experiments were designed to test different vehicles with a representative range of suspension performances, vehicle payloads, axle configurations, inter-axle spacings, vehicle speeds, and road roughness. The most notable variable was the suspensions' wheel load power spectra, of which typical examples are shown in Figures 9 and 10. Yet, despite significant variability in vehicle parameters, spatial correlation coefficients were found to be concentrated between .2 and .5. This result is in agreement with results obtained in weigh-in-motion scale tests where certain scales repeatedly encountered higher than average wheel loads [8].

The experimental results strongly suggest that, in general, wheel loads generated by different types of vehicles are moderately correlated in the spatial domain. Therefore, Eisenman's formula, derived on the assumption that wheel loads are uncorrelated, underestimates pavement wear caused by wheel loads. And, the 95th-percentile-based formula, derived on the assumption that wheel loads are perfectly correlated, overestimates pavement wear caused by wheel loads. Referring to the Tables 1 and 2, it is concluded that the tractor steel-spring walking-beam suspension used in the spatial repeatability experiments produced between 4 and 43% more pavement wear on the smooth road than did the tractor air-spring suspension. On the average road, the percentage increase in pavement wear lies between 37 and 150%.

If wheel loads are moderately correlated in the spatial domain, as the experimental results suggest, then it is quite conceivable that some of the most commonly used unfriendly suspensions produce in excess of 10% more pavement wear on smooth roads than do the road-friendly suspensions, and in excess of 50% more pavement wear on roads of average roughness.

REMAINING ISSUES

There clearly exists a need for a formula that evaluates pavement wear caused by wheel loads as a function of the DLC, the static wheel load and spatial correlation. This formula would provide better estimates of the true level of pavement wear caused by suspensions, and would provide a means of evaluating the effect of anticipated increases in spatial repeatability.

There is also a need to determine how spatial repeatability is expected to change as a result of an increase in use of road-friendly suspensions. An unfortunate consequence of road-friendly suspensions is that they generally have similar and overlapping wheel load power spectra. In particular, the sprung-mass resonance frequencies for road-friendly suspensions typically range between 1.5 and 2.0 Hz, whereas this range is between 2.0 and 3.5 Hz for other suspensions. A group of different types of heavy vehicles with sprung-mass resonance frequencies ranging between

1.5 and 2.0 Hz is expected to produced lower DLCs, but higher spatial correlation, than a group of different heavy vehicles with sprung-mass resonance frequencies ranging between 1.5 and 3.5 Hz. Hence, trade-offs between lower DLCs and higher spatial correlation must be investigated with respect to their resultant effect on pavement wear.

The issue concerning the inherent susceptibility of certain suspension types to produce high levels of spatial repeatability needs to be further investigated. A suspension's susceptibility to produce high levels of spatial repeatability relative to other suspensions depends primarily on its performance at frequencies corresponding to unsprung-mass resonance frequencies. It is suspected that suspensions with independent axles (such as air-spring suspensions) produce higher levels of spatial repeatability than suspensions with dependent axles (such as walking-beam suspensions). Further analysis of the experimental data obtained during the spatial repeatability experiments may provide answers to this question.

The issue concerning potential convergence towards optimum vehicle weights-and-dimensions layouts must be addressed. This is a serious issue, given that the combination of an optimum vehicle weights-and-dimensions layout with road-friendly suspensions, effectively, leads to near-identical vehicles.

The evaluation of the road-friendliness of *vehicle systems* is performed by estimating the accumulated pavement wear caused by all wheels at points along the road [1]. Spatial repeatability between the wheels of road-friendly vehicles are inherently low. As a result, the use of road-friendly vehicles, instead of road-friendly suspensions, may provide a solution to potential problem of high levels of spatially repeatability [2].

The questions surrounding the issue of spatial repeatability are varied and far reaching. However, these questions must be answered to ensure that incentives to encourage the use of road-friendly suspensions, or road-friendly vehicles, produce meaningful reductions in pavement wear.

ACKNOWLEDGEMENTS

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