Replication Of Heavy Truck Dynamic Wheel Loads Using A Road Simulator

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ABSTRACT

A six channel road simulator was utilized at the PACCAR Technical Center to replicate heavy truck dynamic wheel loads. The impetus for investigating the effectiveness of a road simulator for measuring dynamic wheel loads was a desire to develop an easy to use and cost effective test methodology for research and development work on minimizing heavy truck dynamic wheel loads without requiring installation of separate wheel load instrumentation (such as strain gauged axles) on each and every test vehicle.

The road simulator was operated in displacement control, replicating measured road surface profiles. Using instrumented and calibrated axles, wheel loads were measured and compared between the simulator and the actual roads on which the simulator test was based.

Initial test results showed that the road simulator versus road surface generated wheel loads matched reasonably well in the frequency domain. However, road simulator wheel load magnitudes in the rigid body mode frequency range (2 - 4 Hz) were in general less than the field generated wheel loads. Non-rotating versus rotating tire damping is a potential factor causing the reduced road simulator wheel load amplitudes.

INTRODUCTION

It has been widely recognized by both pavement and vehicle engineers that heavy trucks play a major role regarding road damage in the US and Canada. Technical professionals from the PACCAR Technical Center have been members of a team of research scientists and engineers studying the interactions between heavy trucks and pavements since 1988. This research team included members from industry, government, and universities. Represented institutions included the PACCAR Technical Center, the University of Washington, Washington State University, Michigan State University, the University of California at Berkeley, and the Washington State Department of Transportation.

It has been PACCAR's mission to join with researchers from the pavement community and work towards the goal of enhancing the overall efficiency of the highway/vehicle transportation system. PACCAR's contribution to this effort to date has been to: 1) provide a strain gauged section of flexible pavement at the PACCAR Technical Center to study pavement/heavy truck interactions and to validate pavement models, 2) provide test vehicles, personnel, and equipment for pavement strain measurement tests, and 3) provide heavy truck engineering and testing expertise for the research team in interpreting the test data.

In addition to the joint research on heavy truck and pavement interactions, PACCAR has been conducting its own research aimed at reducing the potential road damage caused by heavy vehicles. The focus of this effort has been to investigate and develop a test methodology utilizing a road simulator for the purpose of generating realistic dynamic wheel loads in the test laboratory. This paper documents the results of the PACCAR's road simulator research.

PURPOSE AND SCOPE

The purpose of this research project was to exploit PACCAR's road simulator as a cost effective tool for measuring heavy truck dynamic wheel loads. Others have been successful in using a road simulator for replicating dynamic wheel loads based on control algorithms which matched the vehicle response (and thus the resulting dynamic wheel loads) on a road simulator to the vehicle response on the test road (Hu 1988; de Pont 1993).

This study differs from the above referenced research in that instead of the vehicle response, the road simulator wheel platen vertical displacements were matched to the measured vertical profiles from the roads over which the test vehicle traveled. This approach was investigated because, if it turned out to be successful, future heavy truck development tests studying dynamic wheel loads would be much simpler to perform. No longer would extensive instrumentation and road testing be required to collect vehicle response data for each test vehicle. The costs and time expenditures for these development tests would therefore be significantly reduced.

Typically, road simulation control technology reproduces vehicle responses with extremely high fidelity, since those responses are integral to the test development process. In this application, only the road profiles were used in test development, with wheel load responses merely measured and compared between the simulator and actual roads. Therefore, this approach did not accommodate compensation for differences between static and rolling tire properties. In addition, the road simulator used only vertical inputs. Based on these factors, the dynamic wheel loads between road and simulator were not expected to match precisely. However, because the ultimate use of the test methodology would be to develop "road friendly" trucks, a precise replication of a test vehicle's dynamic wheel load time history on the road simulator was not deemed to be absolutely necessary. It was hypothesized that even if the test methodology accuracy was only sufficient for parametric trend studies on vehicles and vehicle systems, it would still be of value for development testing. For example a large quantity of tests could be performed quickly and cost effectively using the road simulator for a coarse evaluation of design alternative trends with only the most promising alternatives passed on to more thorough test methods.

This study utilized a 6 by 4 class 8 tractor and three different road surfaces at normal highway speeds.

METHODOLOGY

TEST VEHICLE

The test vehicle was a 6 by 4 Peterbilt 359 tractor with a fifth wheel mounted load frame (here after referred to as the PB359). The PB359 was equipped with a 4-spring rear suspension and a multileaf front suspension. Static axle loads were set near the legal maximums. All three axles were instrumented with strain gages (bending bridge configuration) and wheel end accelerometers for measuring dynamic wheel loads as had been done in previous studies (Cebon, 1993). Figure 1 presents a photograph of the test vehicle.

Figure 1. Test vehicle - Peterbilt Model 359

ROAD SURFACES

Three road surfaces were evaluated in this study. Road #1 was constructed with concrete slabs evenly spaced at 15 ft. Road #2 consisted of rough asphalt patched concrete slabs. Road #3 was a newly paved smooth asphalt road.

ROAD PROFILE MEASURES

Road surface profiles were measured using a "South Dakota" (i.e. sonic) type road profilometer owned and operated by the Washington State Department of Transportation. This profilometer and the corresponding data acquisition equipment were mounted to a passenger van. The van was instrumented with accelerometers to compensate for the van's dynamic response while measuring road surface vertical profiles. Both left and right side tracks were simultaneously measured.

THE PACCAR TECHNICAL CENTER ROAD SIMULATOR

The road simulator is a six-channel servo-hydraulic actuator system, capable of applying vertical loads to a test vehicle with up to three axles. Each actuator has a flat table or platen mounted on top of the actuator designed to support a test vehicle tire The PB359 was positioned on top of the platens. Figure 2 presents a photograph of the road simulator.

Figure 2. PB359 on the road simulator

Remote Parameter Control (RPC) software, an iterative convergent feedback actuator control software system from MTS Corporation was used to build the drive files for the road simulator. For each road surface , a drive file was developed which matched the wheel platen vertical displacements to the measured road surface profiles. The phasing of the wheel platens was calculated based on the PB359 speed and wheelbase.

DATA ANALYSIS TECHNIQUES

Both road simulator and test road dynamic wheel load data were analyzed and compared in the time and frequency domains. Time histories and power spectral densities were generated. In addition, the wheel loads were compared from a road damage standpoint utilizing wheel load histograms, the Dynamic Load Coefficient method (DLC) (Sweatman, 1980) and a peak load cumulative damage approach.

RESULTS

The test results were evaluated using the data analysis methods discussed in the Methodology Section above. The following paragraphs discuss the results based on each analysis technique.

TIME HISTORY

As a first step in the analysis, the time histories of the dynamic wheel loads from the road simulator and the test road were compared. Figure 3 contains sample time histories for the three road surfaces for the left side forward drive axle wheel as measured on the road and on the road simulator. Close examination of this time history show similar frequency content but the amplitudes on the road simulator were in general lower than those from the test road.

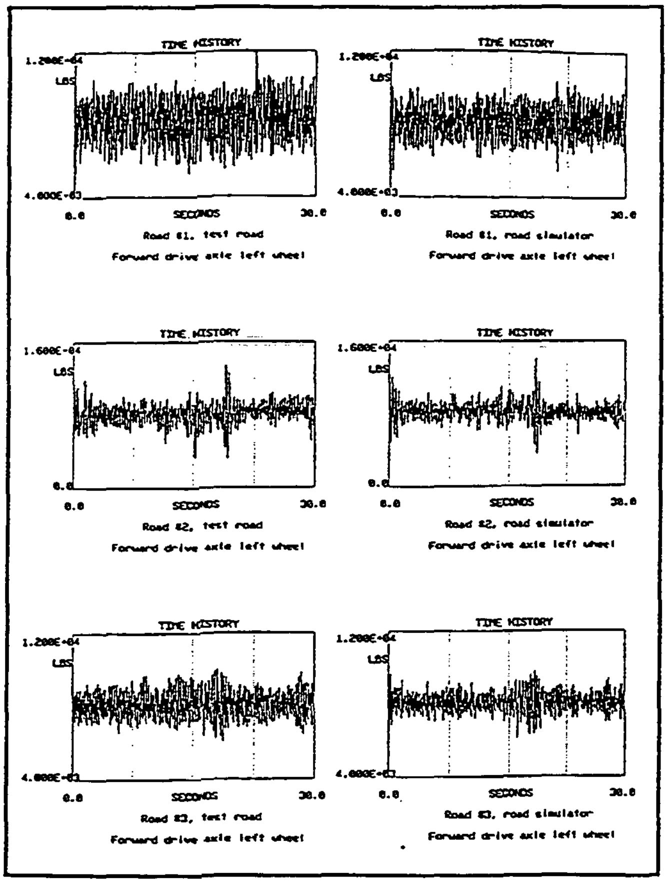

Figure 3, Time history comparisons of left forward drive axle wheel loads

POWER SPECTRAL DENSITY

Comparison of the road simulator and test road dynamic wheel loads in the frequency domain was a logical next step. Figure 4 presents sample power spectral density plots (PSD) for the three road surfaces for the left side forward drive axle wheel as measured on the road and on the road simulator. As shown in the figure, the road simulator did a reasonable job of replicating the test road dynamic wheel load frequency content. However, note that the frequency domain rigid body wheel load magnitudes (at 2 - 4 Hz) for the road simulator were less than or equal to those for the test road. This held true for all three road surfaces and for all wheel locations on the PB359. Also, note that the tire non-uniformity at 7 Hz shown on the test road PSD was not present on the road simulator PSD

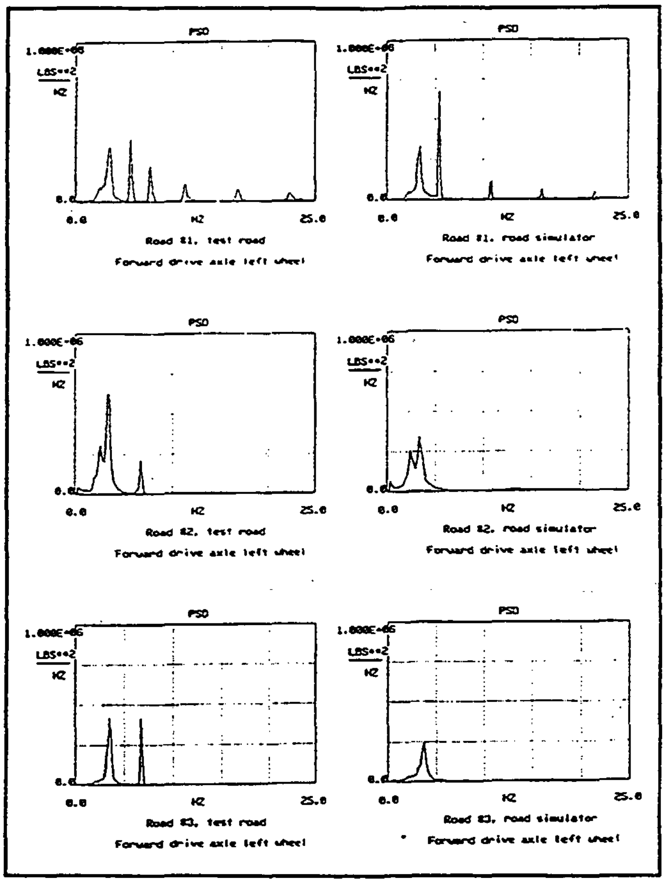

Figure 4, Power spectral density comparisons of left forward drive axle wheel loads

HISTOGRAM

The use of histograms to evaluate the effectiveness of the road simulator in replicating dynamic wheel loads has merit based on the ultimate goal of assessing the contribution of heavy vehicles towards road damage. The histogram gives amplitude ranges and the number of cycles in that range. This information can be used to graphically judge the relative cumulative damage of the dynamic wheel loads generated by the road simulator to those generated by the test road.

Figure 5 presents sample histogram plots for the three road surfaces for the left side forward drive axle wheel as measured on the road and on the road simulator. This plot shows that the overall shape of the corresponding test road and road simulator histograms are similar. It needs to be stressed that the higher load side (i.e. right side) of the histograms for the road surface and road simulator wheel load histograms matched better for some wheel locations compared to others. However, for a given cycle count, the maximum wheel load levels (on the right side of the histogram) are in general lower for the road simulator compared to the test road. This occurrence was not totally unexpected due the lower road simulator generated dynamic wheel load amplitudes previously observed in the time histories and power spectral density plots.

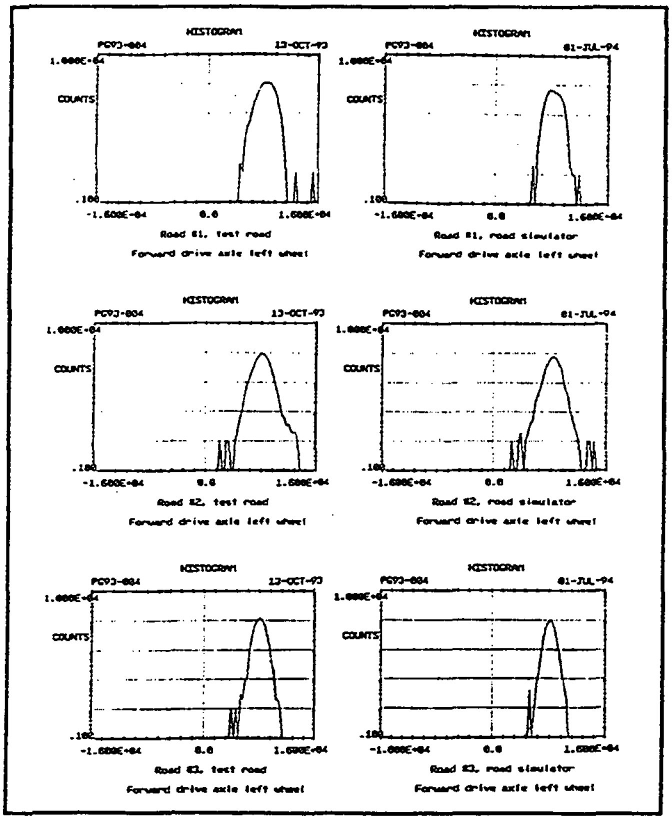

Figure 5, histogram comparisons of left forward drive axle wheel loads

DYNAMIC LOAD COEFFICIENT

The graphical analysis methods performed up to this point showed both similarities and differences in the wheel loads generated by the road simulator compared to the test roads. However, none of the above analysis methods provided a simple and objective scalar measure by which to resolve the issue of how well the road simulator replicated the road damage potential of a heavy truck on the road.

To address this issue, a widely known and accepted objective scalar measure of dynamic wheel load damaging capacity known as the Dynamic Load Coefficient (DLC) was utilized. The DLC is defined as the ratio of the root mean square to the mean of the dynamic wheel force time history.

This study compared the DLCs between the road simulator and the test roads as a means to gage the effectiveness of the road simulator for replicating dynamic wheel loads. Tables 1, 2 and 3 presents a listing of the percent difference between test road and the road simulator DLCs. Note that while the time histories and power spectral densities showed the wheel load magnitudes from the road simulator to be lower than the test road, the DLCs from the road simulator were sometimes greater than the DLCs from the test road. Also, the DLC trends based on wheel position did not appear to agree with the histograms.

Table 1, Dynamic load coefficient comparison between road simulator and Road #1 generated wheel loads

Wheel Location	Highway DLC	Road Simulator DLC	Percent Difference
Forward Left Steer	0.0756	0.0815	7.87 %
Forward Right Steer	0.0885	0.0796	-10.02 %
Forward Left Drive	0.1143	.0913	-20.12 %
Forward Right Drive	0.1155	0.1011	-12.51 %
Rear Left Drive	0.1240	0.1205	-2.82 %
Rear Right Drive	0.1202	0.1092	-9.17 %

Table 2, Dynamic load coefficient comparison between road simulator and Road #2 generated wheel loads

Wheel Location	Highway DLC	Road Simulator DLC	Percent Difference
Forward Left Steer	0.1034	0.0973	-5.95 %
Forward Right Steer	0.1125	0.0941	-16.39 %
Forward Left Drive	0.1144	0.1039	-9.14 %
Forward Right Drive	0.1344	0.1143	-14.97 %
Rear Left Drive	0.1370	0.1239	-9.55 %
Rear Right Drive	0.1317	0.1167	-11.35 %

Table 3, Dynamic load coefficient comparison between road simulator and Road #3 generated wheel loads

Wheel Location	Highway DLC	Road Simulator DLC	Percent Difference
Forward Left Steer	0.0568	0.0685	20.58 %
Forward Right Steer	0.0543	0.0653	20.35 %
Forward Left Drive	0.0779	0.0645	-17.22 %
Forward Right Drive	0.0801	0.0733	-8.46 %
Rear Left Drive	0.0874	0.0856	-2.06 %
Rear Right Drive	0.0874	0.0754	-13.69 %

DYNAMIC LOAD RATIO

Because the DLC analysis did not tend to match the trends shown by the graphical analyses, a second method for reducing the dynamic environment to a scalar value was explored and termed the Dynamic Load Ratio (DLR).

This method raised each peak wheel load in the time history to the fourth power (i.e. a rough application of the fourth power law) (Cebon, 1993). and then summed all the adjusted peak loads for a given time history. This was done for both the road simulator and the test road time histories. The ratio of these sums (i.e. sum of road simulator peaks / sum of road peaks) was calculated to arrive at the DLR. Tables 4, 5, and 6 lists the DLRs from this project.

Table 4, Dynamic Load Ratio comparisons for Road #1

Wheel Location	Dynamic Load Ratio
Forward Left Steer	0.453
Forward Right Steer	0.490
Forward Left Drive	0.342
Forward Right Drive	0.343
Rear Left Drive	0.257
Rear Right Drive	0.265

Table 5, Dynamic Load Ratio comparisons for Road #2

Wheel Location	Dynamic Load Ratio
Forward Left Steer	0.501
Forward Right Steer	0.419
Forward Left Drive	0.593
Forward Right Drive	0.380
Rear Left Drive	0.293
Rear Right Drive	0.262

Table 6, Dynamic Load Ratio comparisons for Road #3

Wheel Location	Dynamic Load Ratio
Forward Left Steer	0.596
Forward Right Steer	0.523
Forward Left Drive	0.563
Forward Right Drive	0.425
Rear Left Drive	0.313
Rear Right Drive	0.289

When the rank order of the DLRs was compared to the histogram plots, the trend matches reasonably well. That is the higher loaded sides of the histograms (i.e. the right side) coincided better for the wheel locations with higher DLRs.

Also, the fact that DLRs were all less than one matches the time history, PSD, and histogram methods which showed that the wheel load magnitudes from the road simulator were less than those from the test roads.

Note that the choice of the exponent (4 in this case) significantly impacts the resultant values of the DLR. Specifically, higher exponents will cause lower DLRs for a given set of road simulator and test road wheel load time histories.. To illustrate, when the exponent is equal to 4, a DLR of approximately 0.66 represents a difference in wheel load magnitude of about 10 percent. For the same 10 percent difference in wheel load magnitude, the DLR would be 0.90 if the exponent were set to 1. Thus, a higher exponent will accentuate smaller differences in wheel loads between a given set of road simulator and test road wheel load time histories.

DISCUSSION

Most of the analysis methods discussed above provided information by which to gauge the effectiveness of using the road simulator in displacement control (i.e. to the road profiles) for replicating heavy truck dynamic wheel loads.

Time histories were useful for evaluating the amplitudes and over all shape of the dynamic wheel loads in the time domain. Power spectral densities verified the frequency content of the wheel loads data. Histograms provided a graphical method by which to compare the distribution of wheel loads based on cycle count. However, none of these methods provided an objective "easy-to-use" method by which to quickly evaluate the road simulator's effectiveness.

Dynamic wheel load time histories and histograms maintained a consistent relationship between the simulator and actual roads, with the simulator somewhat "under-testing" in all cases. However, the DLC approach did not consistently capture this trend.

The Dynamic Load Ratio (DLR) method did appear to track well with the time histories and histograms and holds future promise as an "easy-to-use" method for trending dynamic wheel loads.

It is possible that the DLR could also be redefined for use as an "easy-to-use" tool to trend the "road-friendliness" of heavy truck development on the road simulator. This definition would simply be the ratio of the development truck wheel load summed peaks to a baseline truck.

For heavy truck development work, the choice of the exponent would also be critical, for it will effect the relative significance of the highest wheel loads within a given set of baseline and development truck wheel load time histories.

As an example, consider an arbitrary simplified load time history for a baseline truck wheel compared to four development truck wheel load time histories each containing four peak loads as shown in Table 7.

Table 7, example rank ordering of DLRs based on exponent

	Baseline Truck	Truck #1	Truck #2	Truck #3	Truck #4
Peak 1	2	2	2	1	3
Peak 2	2	2	2	1	3
Peak 3	2	2	2	1	3
Peak 4	4	3	5	4	4
Peak Sum exp=1	10	9	11	7	13
DLR	N/A	0.90	1.10	0.70	1.30
Rank Order	N/A	2	3	1	4
Peak Sum exp=4	304	129	673	259	499
DLR	N/A	0.42	2.21	0.85	1.64
Rank Order	N/A	1	4	2	3

As seen from Table 7, the choice of exponent was critical in its impact on the rank order of the four development truck's DLRs. Therefore, before the DLR method can be utilized for trending future truck development work, the correlation of the DLR approach to road damage would have to be validated. This could possibly be accomplished via computer analyses utilizing the currently available pavement models.

CONCLUSIONS

The following conclusions can be drawn from this study.

1) The use of road profile measurements for generating road simulator drive files for use in the development of "road friendly" heavy trucks appears to hold some promise for success. The results showed good replication of the wheel load frequency content.

2) The Dynamic Load Ratio (DLR) method appears to provide a reasonable "easy-to-use" objective measurement technique for evaluating the effectiveness of the road simulator in replicating dynamic wheel loads. In addition, the DLR method for the most part agreed with the time history and histogram analyses and may also be adaptable for heavy truck "road friendliness" development work.

The following issues need to be resolved for the road simulator method to be successful as a tool for developing "road friendly" heavy trucks:

1) The dynamic wheel load magnitudes generated by the road simulator were lower compared to loads generated by the test roads. The effect of rolling versus stationary tire damping might help explain the magnitude discrepancy. This was not evaluated in this study, but is well within the realm of contemporary road simulator control technology.

2) The Dynamic Load Coefficient analyses did not appear to trend very well with the histogram analysis.

3) The results from the histogram method and the Dynamic Load Ratio approach appear to trend consistently with wheel location. This suggests that vehicle effects may play a major roll in the effectiveness of the road simulator method. Thus, different vehicles need to be evaluated.

4) The Dynamic Load Ratio method should be investigated further using pavement models to validate that the DLR trends well with pavement damage.

Although it was not relevant to road simulator research, it is worth noting that the wheel load magnitudes related to a tire non-uniformity for the left front drive wheel (7 Hz) on smooth road were comparable to the wheel load magnitudes attributable to the rigid body modes (2 - 4 Hz) for this test vehicle. The fact that this wheel/tire generated input was not severe enough to be a noticeable objectionable ride issue but still caused a dynamic wheel load component on par with the wheel load components due to the rigid body modes was surprising. Furthermore, the tire loads occurred at approximately twice the frequency of the rigid body loads and therefore would be more damaging to the pavement in this case. This observation suggests that tire/wheel non-uniformity issues might be worthy of further investigation regarding their contribution to the dynamic loading of pavements.

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REFERENCES

Hu, G. (1988) "Use of a Road Simulator for Measuring Dynamic Wheel Loads", Paper 881194, submitted to the Society of Automotive Engineers

de Pont, J, 1993 "Rating heavy vehicle suspensions for "road friendliness"", Heavy Vehicle Systems, Special Series, Int. J. of Vehicle Design, Vol. 1, No. 1, pp. 20 - 33.

Cebon, D. (1993) "Interaction between heavy vehicles and roads", Appendix A, pp. 77 - 78, The thirty-ninth L. Ray Buckendale Lecture, Paper 930001, submitted to the Society of Automotive Engineers

Sweatman, P, (1980) "Effect of heavy vehicle suspensions on dynamic road loading", Research Report ARR No. 116

Cebon, D. (1993) "Interaction between heavy vehicles and roads", section 1.3.3 pp. 8 - 10, The thirty-ninth L. Ray Buckendale Lecture, Paper 930001, submitted to the Society of Automotive Engineers