Effects of Dynamic Loads on Flexible Pavements

T. PAPAGIANNAKIS, R. C. G. HAAS, J. H. F. WOODROOFFE, AND P. A. LEBLANC

Dynamic axle loads were measured with an instrumented vehicle, and pavement performance was modeled using a modified version of VESYS-III-A. The experiment involved five levels of pavement roughness, three levels of vehicle speed, and two suspension types—air and rubber. A method was proposed for modeling the impact of the repetitive in-space dynamic loads experienced by AASHO Road Test sections. It consisted of dividing the load frequency distribution experienced by each section into segments and assigning segment combinations from the axles of a vehicle to pavement subsections. The method yielded a considerable improvement in performance prediction accuracy. Another part of the study examined the impact of suspension type on pavement performance by assuming that dynamic loads are random in space. The load frequency distributions obtained for the highest vehicle speed tested were used for this purpose. Comparisons were based on the area contained between the performance curve and a minimum PSI value. For the roughest section, the rubber suspension caused 17 to 22 percent more damage than the static load, depending on the terminal PSI value assumed. Similar values calculated for the air suspension ranged between 4 and 8 percent. Results were sensitive to the way the tire inflation pressure was handled in modeling dynamic load.

The AASHO Road Test was one of the earliest efforts to evaluate the impact of axle loads on pavement performance (*1*). Special studies conducted during the Road Test provided measurements of dynamic axle loads for a variety of vehicle speeds, suspension types, and levels of pavement roughness (*2*). A tire pressure transducer was used for the dynamic load measurements, and it was calibrated using a Weigh-in-Motion (WIM) scale. The general trend observed was that higher levels of pavement roughness and/or vehicle speed result in an increase in the dynamic load variation. There were no further efforts, however, to account for the effect of the dynamic axle loads on pavement performance.

Whittemore et al. (*3*) presented an NCHRP-sponsored study dealing with a variety of experimental and analytical methods for determining dynamic axle loads on pavements. The study evaluated three different methods for measuring dynamic axle loads: a tire pressure transducer, a combination of strain gauges and accelerometers on the axles, and a wheel-force transducer mounted on the hub of one of the tires. The latter was developed by General Motors for the study. It was concluded that the tire inflation pressure is not in phase with the dynamic load, and therefore the tire inflation pressure transducer was considered unsuitable for dynamic load measurements. The other two systems yielded comparable results in measuring dynamic loads. Efforts to model dynamic axle loads were limited to an analog model of a quarter-car which yielded estimates of dynamic load within 15 percent of the measured values.

Recently, there has been a renewed interest in the area of dynamic axle loads and their impact on pavements. Sweatman (*4*), Woodrooffe et al. (*5*), and Woodrooffe and Leblanc (*6*) examined the vehicle parameters affecting dynamic axle loads. Sweatman used the General Motors wheel-force transducer, whereas Woodrooffe and co-workers used a combination of strain gauges and accelerometers. Both studies considered factors such as axle configuration, suspension type, tire pressure, vehicle speed, and pavement roughness. The primary objective of those studies was to optimize vehicle design rather than to evaluate the pavement damage aspect of dynamic axle loading. Those studies established that pavement roughness can induce substantial variations in axle load. They also showed that the suspension type significantly affects the magnitude of dynamic axle load variation. Furthermore, they found that vehicle speed causes an increase in the magnitude of dynamic load variation for all suspension types tested.

Gorge (*7*) and Addis et al. (*8*) examined the relationship between dynamic axle load and pavement response parameters. Gorge used a number of different methods for measuring dynamic loads, such as an accelerometer arrangement, a combination of strain gauges and accelerometers, and a wheel-force transducer. Addis et al. used an optical tire deflection device calibrated to yield tire load from tire deflection. In both studies, strain gauges embedded in the pavement layers were used to measure pavement response. Although these efforts established a good relationship between dynamic load and pavement response parameters, they stopped short of relating dynamic load to pavement performance.

A joint study has been undertaken by the University of Waterloo and the National Research Council of Canada to fill this gap. The objective was to examine the impact of roughness-induced dynamic axle load on pavement performance. Dynamic axle loads were measured using the instrumented vehicle developed by the Research Council in the context of the Roads and Transportation Association of Canada (RTAC) Vehicle Weights and Dimensions Study (*5, 6*). Pavement performance was modeled using a modified version of VESYS-III-A (*9*). Predictions of pavement performance were compared to observations from a number of AASHO Road Test sections. The basic hypothesis tested was that proper

T. Papagiannakis, College of Engineering, Memorial University of Newfoundland, St. John's, A1B 3X5, Canada. R. C. G. Haas, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada. J. H. F. Woodrooffe and P. A. Leblanc, Vehicle Dynamics Laboratory, National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada.

consideration of dynamic axle loads improves the accuracy of pavement performance predictions.

This paper reports on some of the findings of the study documented by Papagiannakis (*10*). Three major parts of the study are presented. The first describes the experimental program and summarizes its findings. The second deals with the methodology followed for simulating the performance of the AASHO Road Test sections. The third studies the impact of suspension type on pavement performance.

EXPERIMENTAL PROGRAM

The dynamic load testing was conducted in two phases. First, exploratory tests were carried out in May 1986 as part of the RTAC Vehicle Weights and Dimensions Study. The emphasis in this phase of the testing was on the dynamic behavior of a leaf spring suspension, which was the type of suspension used in the AASHO Road Test. Second, an experiment was conducted in June 1987 to explore the dynamic properties of the two suspension types that were shown to exhibit extreme dynamic behavior—an air and a rubber suspension (*5, 6*). The following sections briefly describe the two experimental phases of the study and present some of the findings.

Experimental Phase One, May 1986

The vehicle runs for the RTAC Vehicle Weights and Dimensions Study were conducted on three pavement sections in Ottawa, Ontario. Two local streets and a freeway section were selected, representing a range of pavement roughnesses. Pavement roughness was measured on all three sections with a Mays Ride Meter (MRM) expressed in in./mi. In addition, roughness profile data were obtained for the two local streets using the rod-and-level technique. Elevation was measured in both wheelpaths at 0.5-m intervals. The profile data were intended for calculating slope variance (SV), which was the roughness statistic used in the AASHO Road Test.

Study of the dynamic load waveforms of the leaf spring suspension revealed two important findings. First, the load waveforms of the lead and the trailing axles of a tandem assembly are approximately in phase and have roughly equal amplitudes as shown in Figure 1. As a result, load sharing between tandem axles is not important in evaluating their impact on pavements, and therefore the sum of the load of a pair of tandem axles can be treated as a single load. Second, the predominant oscillation frequency is on the order of 3 Hz and remains constant with changes in pavement roughness and/or vehicle speed as shown in Figures 2 and 3. These observations are important in modeling the spatial arrangement of dynamic load waveforms for pavement roughness levels increasing over time.

A number of problems were experienced during the first phase of the experiment. First, the calculated variance in the measured pavement elevation slope was not comparable to the SV calculated from the CHLOE Profilometer. This is probably because the actual dynamics of the device were not taken into account. Indeed, estimates of SV made from measured profiles were not equivalent to the outputs of the old instruments (*11*). The problem was resolved by using the dynamic load data obtained in the special AASHO Road Test study mentioned earlier. A regression equation was fitted to the coefficient of variation of the dynamic load for a vehicle speed of 48 kph (CV) and the pavement roughness (SV) as shown by Equation 1. The general form of the relationship proposed by Sweatman (*4*) was used for this purpose.

$$CV = 3.974\ SV^{0.5} \qquad (1)$$

Another problem was realized in relating the load waveform to locations along the length of the pavement. To alleviate this problem, an axle detector was developed for the second phase of the experiment. Finally, it was decided to abandon the rod-and-level technique for profile measurements in favor of a profilometric roughness device. For this purpose, a Surface Dynamics Profilometer was used (*12*).

Experimental Phase Two, June 1987

The second phase of the experiment involved five levels of pavement roughness and three levels of vehicle speed. Five

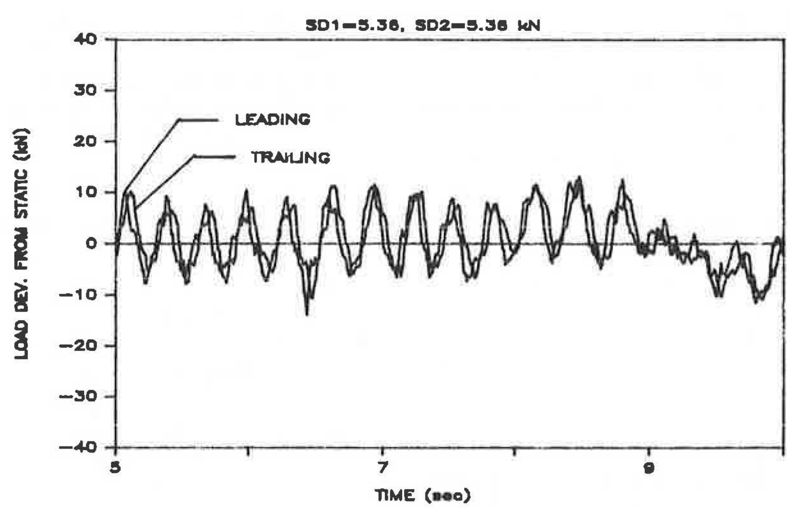

FIGURE 1 Dynamic load waveform of a leaf spring suspension, V = 40 kph, R = 73 in./mi.

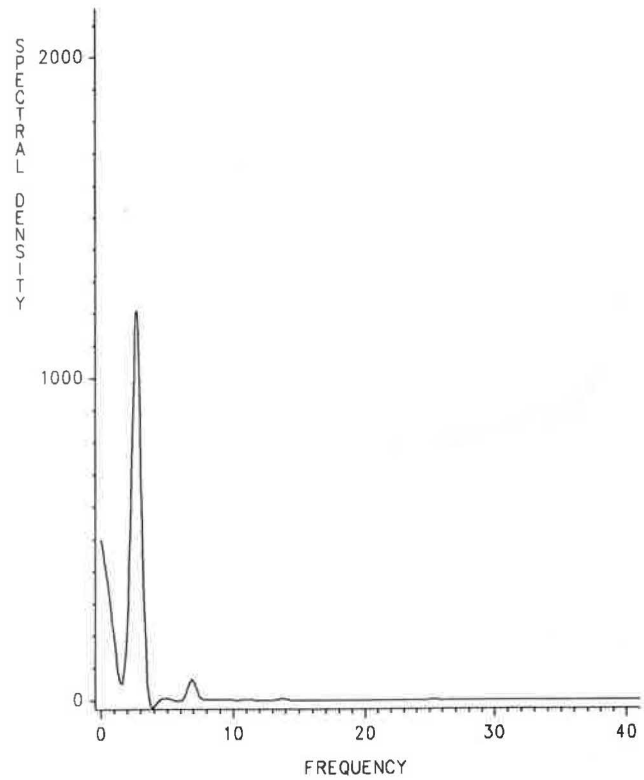

FIGURE 2 Spectral density of the leaf spring suspension, V = 80 kph, R = 73 in./mi.

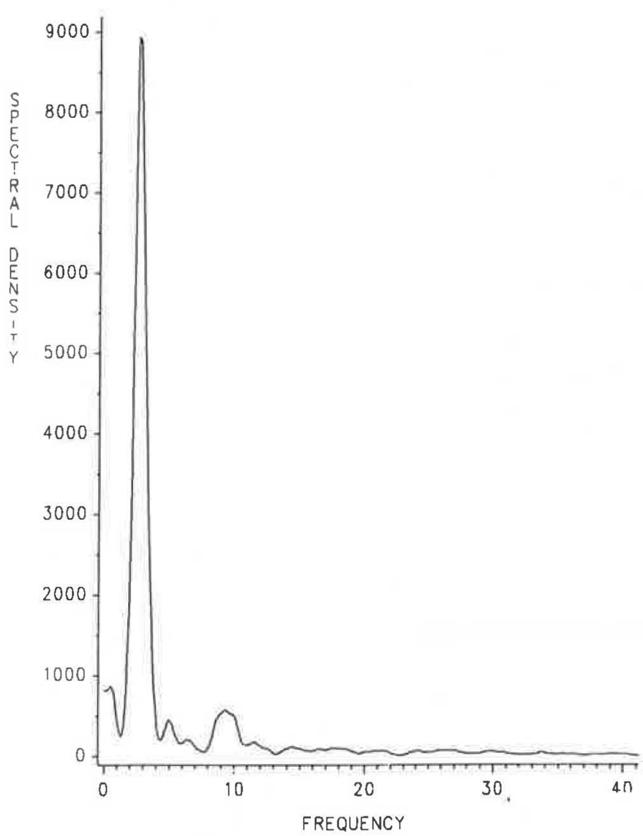

FIGURE 3 Spectral density of the leaf spring suspension, V = 80 kph, R = 217 in./mi.

FIGURE 4 Axle detector and transmitter assembly.

pavement sections were selected in the vicinity of Ottawa, Ontario, representing a wide range of pavement roughnesses. A laser-based axle detector coupled with a transmitter-receiver assembly was built (Fig. 4). Its function was to transmit signals to the instrumented vehicle every time the laser beam was interrupted by an axle. A typical output of this device is shown in Figure 5. The laser beam was set across the road at the beginning of each section, and a fifth wheel on the vehicle provided exact distance measurements. In addition to the 15 runs mentioned above, a number of replicate runs were conducted to study the spatial arrangement of successive dynamic load waveforms.

The results of the second phase of the experiment are summarized in Table 1 in the form of the standard deviation (SD) of the dynamic load generated by each suspension type. The profile data were used to produce simulated MRM indices at 50-m intervals according to the procedure described by McQuirt et al. (*13*). For each section, the MRM indices were averaged to produce a representative value which is shown in Table 1. The observed range in SD was between 8 and 42 kN depending on suspension type, pavement roughness, and vehicle speed. Curves were fitted to the experimental data obtained for the air and the rubber suspensions (Equations 2 and 3, respectively).

$$SD = 0.087V^{0.398} R^{0.725}, (r^2 = 0.797) \qquad (2)$$

$$SD = 0.005V^{1.265} R^{0.671}, (r^2 = 0.903) \qquad (3)$$

The dynamic behavior of the two suspensions is quite different, mainly their response to vehicle speed, as indicated by the magnitudes of the exponents of speed in equations 2 and 3. The effect of vehicle speed is further demonstrated by plotting SD vs. speed for the roughest section, as shown in Figure 6. For vehicle speeds higher than 40 kph, the rubber suspension yields significantly higher load variation than the air suspension.

The replicate runs revealed an important finding. Dynamic load waveforms from replicate runs are repeatable in space as shown in Figure 7. A similar observation was made by Addis et al. (*8*). Although this loading condition is clearly not the case for pavements under normal traffic, it was typical of the loading experienced by AASHO Road Test sections. In

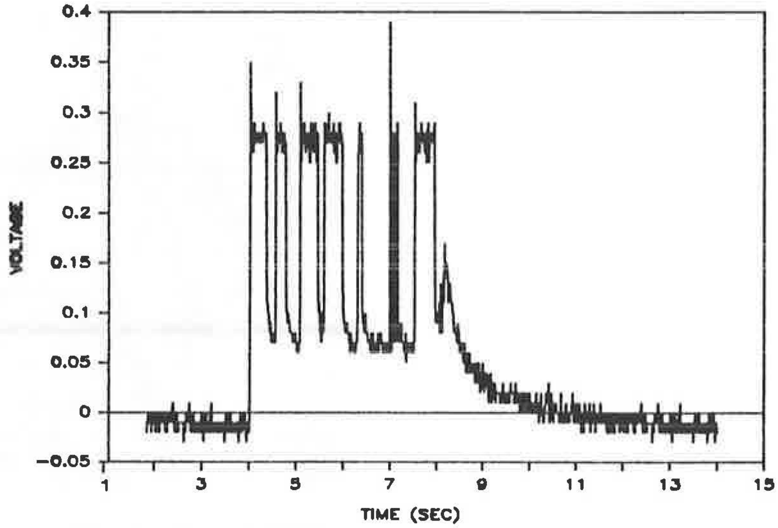

FIGURE 5 Output of the axle detector.

the latter, a particular vehicle type carrying a given payload and traveling at a constant speed was assigned to each loop or lane. Thus, a loading condition resulted where certain points on the pavement experienced loads consistently higher than the static whereas others experienced loads consistently lower than the static. This localized application of the dynamic load is taken into account in simulating the performance of AASHO Road Test sections as subsequently described.

TABLE 1 RESULTS OF PHASE TWO OF THE EXPERIMENT

RUN	SITE	ROUGH. (Mays)	SPEED (km/h)	OBSERV.	LENGTH (m)	S.D.(kN) RUBBER	AIR
29			40	7069		8.04	8.07
30	1	56	60	4440	746.17	10.87	6.94
31			80	3400		14.28	7.40
21			40	7207		11.06	9.44
22	2	87	60	4527	760.74	18.76	8.66
24			80	3467		28.17	11.01
13			40	7286		10.86	10.40
14	3	96	60	4576	769.08	14.49	11.30
12			80	3505		30.11	13.67
3			40	4913		14.76	12.60
4	4	115	60	3085	518.59	16.81	19.07
40			80	2363		33.57	19.46
16			40	6423		22.15	15.65
17	5	201	60	4034	677.98	27.06	22.11
20			80	3090		42.55	21.08

Note 1: Static loads on the tandem groups are 205.52 and 204.54 kN for the drive and trailer axles, resp.

Note 2: 100 observations correspond to 1 sec

ANALYTICAL PROGRAM

The analytical program of the study had two main objectives. The first was to demonstrate that consideration of dynamic axle loads can improve the accuracy of pavement performance predictions. For this purpose, the performance of a number of AASHO Road Test sections was analyzed by simulating the dynamic axle loads experienced over their service lives. The second objective was to study the impact of suspension type on pavement performance. For this purpose, the experimental dynamic load data obtained for the air and the rubber suspensions were input into VESYS, and comparisons of pavement performance predictions were made.

Simulation of AASHO Road Test Sections

Ten AASHO Road Test sections were selected for the performance simulations. The selected sections included six that developed severe roughness (i.e., SV higher than 10×10^{-6}) and four that remained relatively smooth through their service lives (i.e., SV lower than 10×10^{-6}). The material properties documented by Rauhut et al. (*14*) were used throughout. The temporal variation in material properties was accommodated by distinguishing five "seasons." For each season, the spatial variation in material properties was described by their coefficients of variation.

The analysis of the sections that remained smooth was intended for calibration of the VESYS simulations with respect to material properties. These sections were analyzed by assuming that axle loads are static. Since a number of the sections analyzed carried 5-axle vehicles, it was decided to modify VESYS-III-A to accommodate the overlapping influence of tandem axles. For this purpose, the "rainflow" method described in ASTM E1049-85 was followed (*15*).

Another modification considered necessary was the addition of a model describing the component of pavement rough-

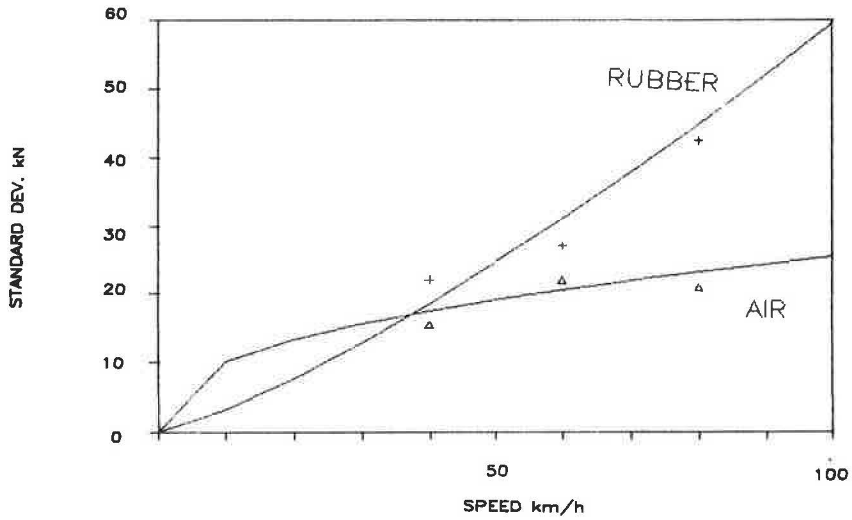

FIGURE 6 Impact of vehicle speed on axle load variation.

ness caused by fatigue cracking. Two relationships were used, the first relating the damage index (DI) to the area cracked (A_c) and the second relating the area cracked to pavement roughness, SV. Equation 4 describes the first relationship as proposed by Rauhut et al. (*14*), and Equation 5 describes the other relationship, which was developed through regression from the data on the 10 sections analyzed.

$$A_c = 1.91e^{3.958DI} \quad (4)$$

$$SV = A_c^{0.556} \quad (5)$$

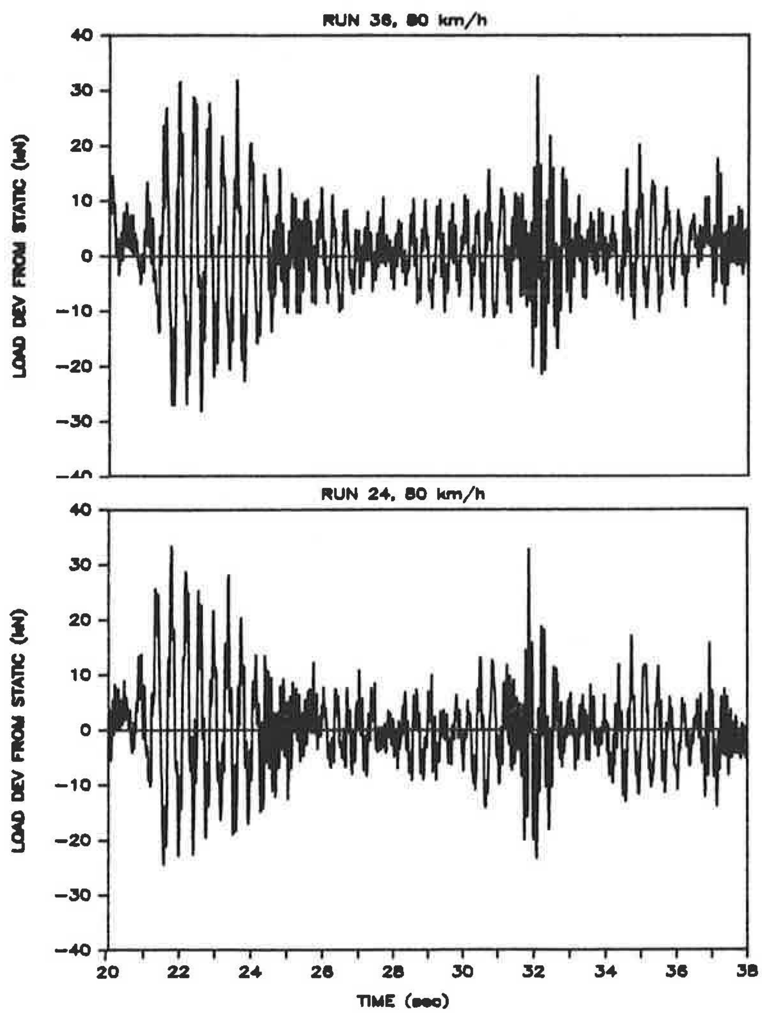

FIGURE 7 Spatial repetitiveness of dynamic load.

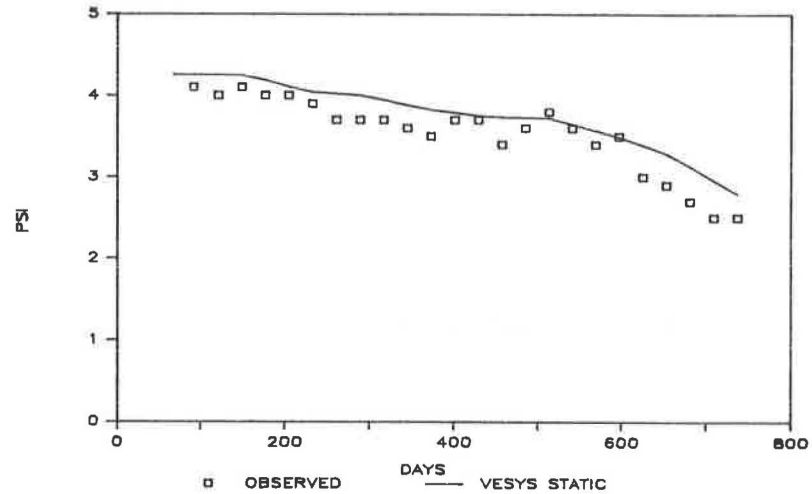

FIGURE 8 Predicted vs. observed performance, section 312.

The results of the analysis demonstrated that VESYS can provide fairly accurate predictions of distress and performance for sections that remained relatively smooth through their service lives. An example of observed vs. predicted PSI values for one of the smooth sections is shown in Figure 8.

The analysis of the sections that developed severe roughness was carried out by taking into account the spatial repetitiveness of dynamic load from replicate vehicle passes. The analysis concentrated on the pavement length over which an axle completes a load cycle. Given a frequency of load variation of 3 Hz and a vehicle speed of 58 kph (35 mph), this length was calculated as 5.2 m. The methodology followed consists of dividing the 5.2-m length into six subsections and assigning load segments from the axles of the passing vehicle to each subsection. The procedure involved the following steps:

1. Coefficients of Variation (CV) of dynamic axle load were estimated on the basis of the observed pavement roughness, using Equation 1. For each section, three time intervals were distinguished over which the CV of the load was considered constant.
2. For each time interval, a frequency distribution of dynamic load was assumed. A normal distribution was assumed for CV values below 15 percent and a trapezoid distribution for CV values higher than 15 percent.
3. Each load frequency distribution was divided into six load segments of equal probability, and the average value of load in each segment was calculated by numerical integration as shown in Figure 9. A combination of load segments from the axles of a vehicle was assigned to each subsection on the basis of axle spacing as shown in Figure 10.
4. VESYS simulations were performed for each subsection to yield estimates of pavement distress and performance (i.e., DI, SV, rut depth, and PSI vs. time).
5. The distress predictions of the subsections were combined into distress and performance predictions for the entire section. This was done by averaging the rut depth of subsections, while assuming that the subsection with the highest DI

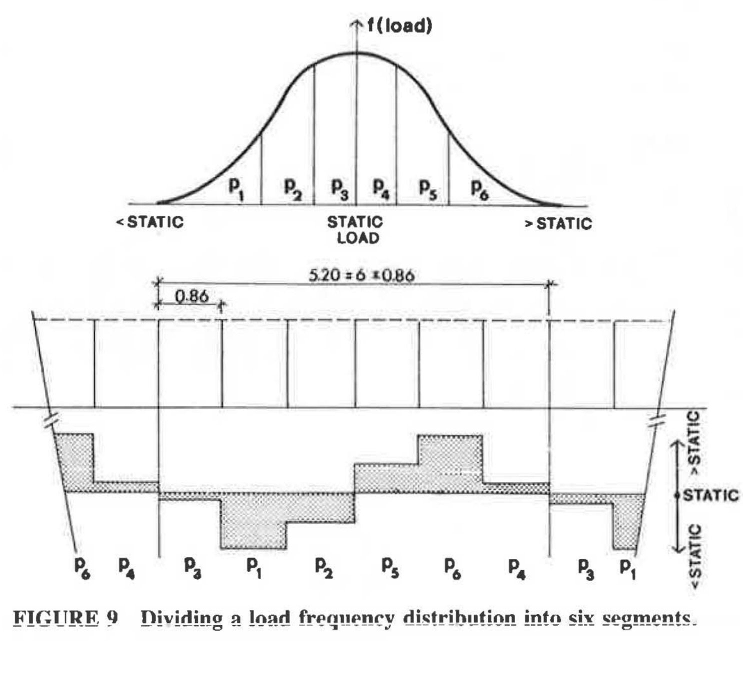

FIGURE 9 Dividing a load frequency distribution into six segments.

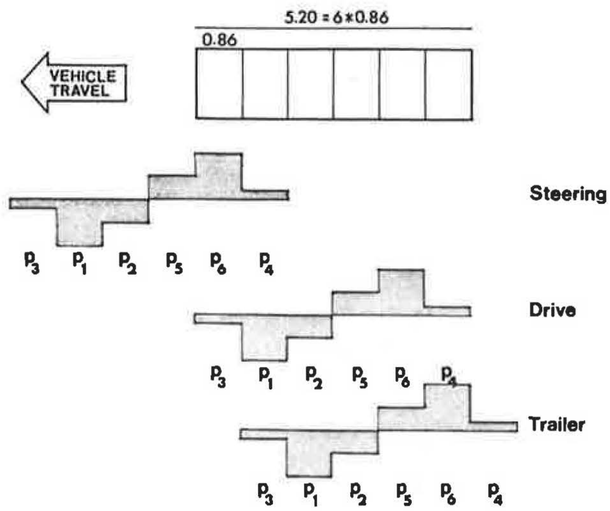

FIGURE 10 Assigning load segments to subsections.

determines the amount of cracking and therefore the pavement roughness on the entire section.

Another modification to VESYS-III-A accommodated the increasing in-time axle load variation. An algorithm was used where three independent sets of pavement distress parameters were calculated and subsequently superimposed to produce overall distress and performance predictions. Examples of the results of the analysis are shown in Figures 11, 12, and 13. Overall, the described methodology considerably improved the performance predictions for four of the six rough sections analyzed, whereas only a marginal improvement was realized for the other two sections.

Impact of Suspension Type on Pavement Performance

The objective of this part of the study was to evaluate the impact of suspension type on pavement performance under normal traffic. As pointed out earlier, vehicles under normal

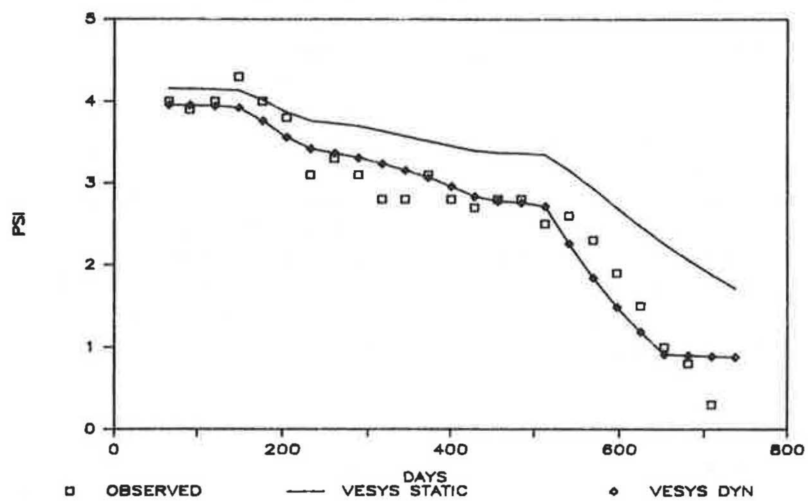

FIGURE 11 Predicted vs. observed performance, section 331.

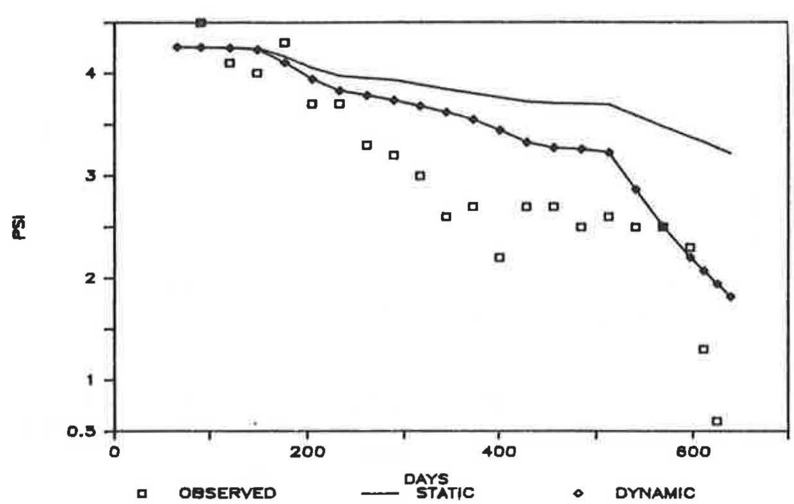

FIGURE 12 Predicted vs. observed performance, section 469.

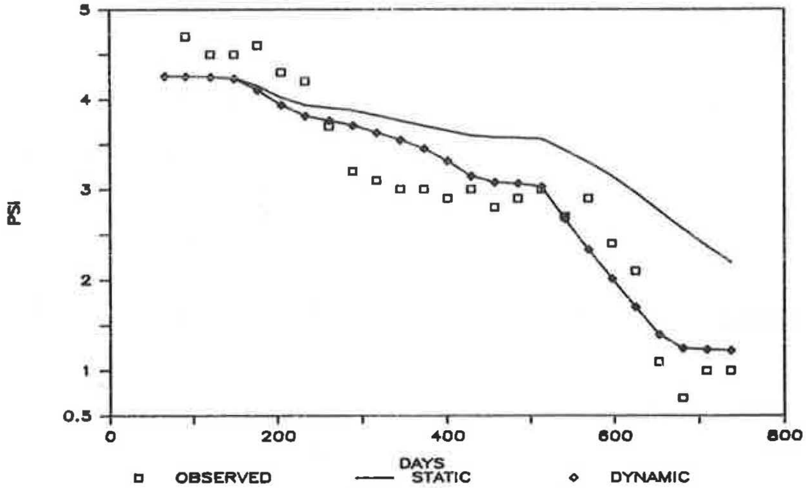

FIGURE 13 Predicted vs. observed performance, section 479.

traffic apply dynamic axle loads randomly in space. Under these conditions, dynamic axle loads can be input into VESYS as their frequency distributions. The analysis focused on the experimental data of the air and the rubber suspensions obtained for the highest vehicle speed tested (80 kph). Two modifications to VESYS-III-A were considered necessary. The first was the previously described algorithm that accounts for the pavement roughness caused by fatigue cracking. The second consisted of increasing the dimension of a number of arrays to allow input of a combination of 12 load intervals and 5 seasons (i.e., a dimension of 60 replaced the original dimension of 25). Each load interval was input as a circular tire imprint of uniform pressure which was assumed to be equal to the tire inflation pressure. Under dynamic conditions, the tire inflation pressure was assumed to vary with the load within 20 percent of the pressure under static conditions. However, VESYS is sensitive to the tire inflation pressure specified rather than to the tire imprint radius, as suggested by other studies (*16*). As a result, the performance predictions depended to a large extend on the assumption used for the tire inflation pressure variation under dynamic conditions.

The pavement performance predictions for the air and rubber suspensions were compared to the performance predictions obtained under static load. The comparisons were based on the calculated "areas" under the performance curves. These were obtained by summing the ordinate segments contained between a performance curve and a selected terminal present serviceability index (PSI). Minimum PSI values of 2.0 and 2.5 were considered. The sums obtained for each suspension type and level of pavement roughness were divided by the sum obtained under static load. The results were plotted in the form of additional pavement damage vs. pavement roughness (Figures 14 and 15 corresponding to terminal PSI values of 2.0 and 2.5, respectively). The analysis of the load data for the roughest section, for example, revealed that the rubber suspension caused 17 to 22 percent more damage than the static load, depending on the assumed value of terminal PSI. Similar values calculated for the air suspension ranged between

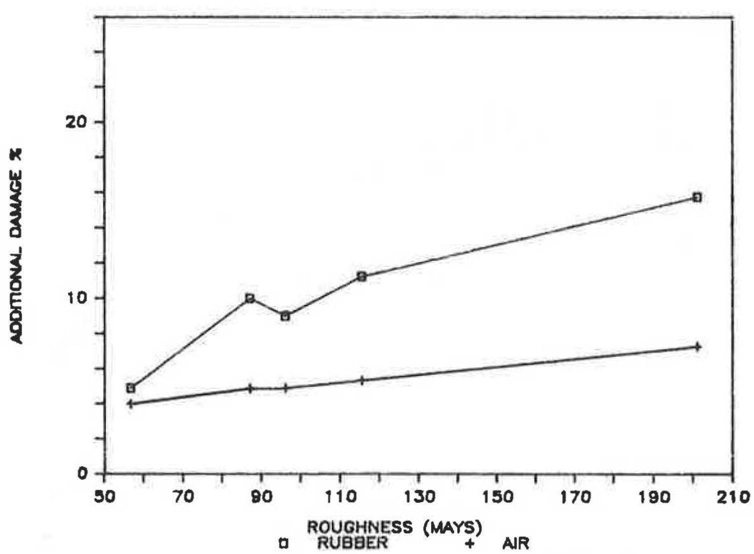

FIGURE 14 Impact of suspension type on pavement performance: terminal PSI = 2.0.

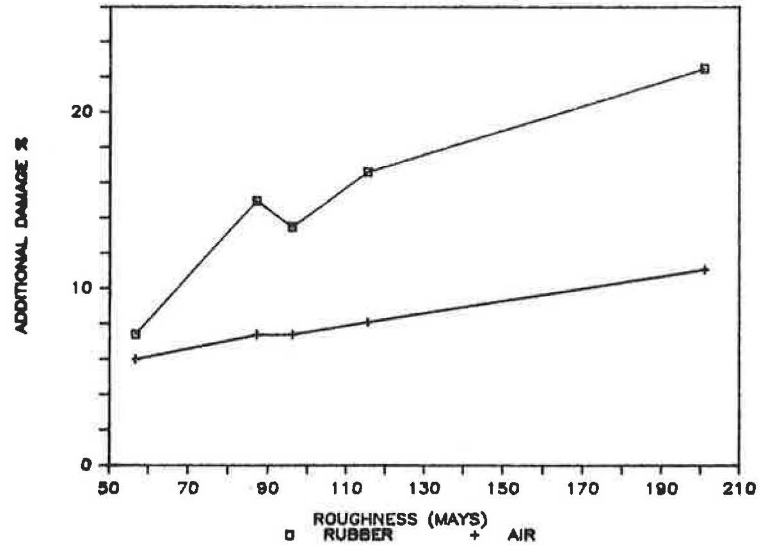

FIGURE 15 Impact of suspension type on pavement performance: terminal PSI = 2.5.

4 and 8 percent. These results depended on the assumption used for the variation in tire inflation pressures, as pointed out earlier.

SUMMARY

The major findings of the experimental part of the study are:

1. For the leaf spring suspension tested, the dominant frequency of the load variation was 3 Hz. This frequency remained constant with changes in vehicle speed and pavement roughness.
2. Axle load variation depends on suspension type, pavement roughness, and vehicle speed. The range of the observed standard deviations of dynamic load was between 8 and 42 kN.
3. The load variation of the air suspension is less sensitive to vehicle speed than the load variation of the rubber suspension.
4. Replicate runs generate load waveforms repetitive in space.

The last observation suggests that for replicate runs, certain points on the pavement experience loads consistently higher than the static whereas others experience loads consistently lower than the static. It was pointed out that although this loading condition is not the case for pavements under normal traffic, it was typical of the loading experienced by AASHO Road Test sections.

The analytical part of the study had two main objectives: first to demonstrate that consideration of dynamic axle loads can improve the accuracy of pavement performance predictions, and second to study the impact of suspension type on pavement performance. The first objective was addressed by modeling the performance of a number of AASHO Road Test sections and by treating dynamic load as being repetitive in space. This method yielded significant improvements in performance prediction accuracy for four of the six rough sections analyzed.

The second objective was addressed by modeling pavement performance under the experimental dynamic load data obtained for the air and the rubber suspensions. That part of the study considered dynamic axle loads as being random in space. The load frequency distributions obtained for the highest vehicle speed tested were input into a modified version of VESYS-III-A. Pavement performance predictions were compared on the basis of the areas contained between the performance curve and a terminal PSI value. The results of the analysis indicated that the rubber suspension caused substantially higher pavement damage than the air suspension. This trend became more pronounced at higher levels of pavement roughness.

It was suggested that the pavement performance predictions obtained by VESYS-III-A depend to a large extent on the inflation pressure of the tires. Since little is known about the variation of the tire inflation pressure under dynamic conditions, it is recommended that similar future experiments include measurements of tire inflation pressures.

ACKNOWLEDGMENTS

The technical and financial support provided by the Ministry of Transportation of Ontario is gratefully acknowledged. Special thanks are extended to W. A. Phang for his kind support and advice throughout the course of this study.

REFERENCES

1. *Special Report 61E: The AASHO Road Test—Report 5, Pavement Research,* HRB, National Research Council, Washington, D.C., 1962.
2. *Special Report 61F: The AASHO Road Test—Report 6, Special Studies,* HRB, National Research Council, Washington, D.C., 1962, pp. 45–47.
3. A. P. Whittemore, J. R. Wiley, P. C. Schultz, and D. K. Pollock. *NCHRP Report 105: Dynamic Pavement Loads of Heavy Highway Vehicles.* HRB, National Research Council, Washington, D.C., 1970.
4. P. F. Sweatman. *A Study of Dynamic Wheel Forces in Axle Group Suspensions of Heavy Vehicles.* Special Report SR No. 27. Australian Road Research Board, 1983.

5. J. H. F. Woodrooffe, P. A. Leblanc, and K. R. LePiane. *Effect of Suspension Variations on the Dynamic Wheel Loads of a Heavy Articulated Vehicle.* Vehicle Weights and Dimensions Study, Technical Report, Vol. 11, Road and Transportation Association of Canada, 1986.
6. J. H. F. Woodrooffe and P. A. Leblanc. *The Influence of Suspension Variations on Dynamic Wheel Loads of Heavy Vehicles.* Paper 861973. Society of Automotive Engineers, 1986.
7. W. Gorge. *Evaluation of Research Efforts Concerning the Influence of Commercial Vehicle Development on the Road Fatigue.* German Automotive Technical Research Association. Summary and Evaluation of the Reports 900, 938, and 992 of the Testing Bureau for Road Engineering, Technical University of Munich, 1984.
8. R. R. Addis, A. R. Halliday, and C. G. B. Mitchell. Dynamic Loading of Road Pavements. Presented at International Symposium on Heavy Vehicle Weights and Dimensions, Kelowna, British Columbia, June 8–13, 1986.
9. Predictive Design Procedures. *VESYS User's Manual.* FHWA Report RD-77-154, 1977.
10. A. T. Papagiannakis. *Impact of Roughness-Induced Dynamic Load on Flexible Pavement Performance.* Ph.D. dissertation. Department of Civil Engineering, University of Waterloo, 1988.
11. M. W. Sayers, T. D. Gillespie, and C. A. V. Queiroz. *The International Road Roughness Experiment; Establishing a Correlation and a Calibration Standard for Measurements.* World Bank Technical Paper No. 45, 1986.
12. E. B. Spangler and W. J. Kelly. Road Profilometer—A Method for Measuring Road Profile. In *Highway Research Record 121,* HRB, National Research Council, 1965, pp. 27–54.
13. J. E. McQuirt, E. B. Spangler, and W. J. Kelly. *Use of the Inertial Profilometer in the Ohio DOT Pavement Management System.* Special Technical Publication 929, American Society for Testing of Materials, 1986.
14. J. B. Rauhut, R. L. Lytton, and M. I. Darter. *Pavement Damage Functions for Cost Allocation,* Vols. 1, 2, and 3. Report No. FHWA/RD-84/018, /019, and /020, 1984.
15. *Cycle Counting in Fatigue Analysis.* ASTM E1049-85, pp.836–848, 1985.
16. J. B. Rauhut, J. C. O'Quin, and W. R. Hudson. *Sensitivity Analysis of FHWA Structural Model VESYS-II-M, Preparatory and Related Studies,* Vol. 1. Report FHWA-RD-76-23, 1976.

Publication of this paper sponsored by Committee on Flexible Pavement Design.