Influence of Vehicle Speed on Dynamic Loads and Pavement Response

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Weigh-in-motion systems have been used extensively to measure dynamic loads imparted by traffic vehicles. One of the major uses of these load data is to evaluate the equivalent single-axle loads (ESALs) generated by each load level. The cumulative ESALs are then used in the design or rehabilitation procedures, or both, for the existing road. In situ pavement response parameters, such as the strains at the bottom of the asphalt concrete layer, can also be used to evaluate ESALs. The findings of a research program aimed at evaluating the effect of vehicle speed on the measured dynamic loads and pavement response are documented. The data were measured through a full-scale field experiment. The analyses of the data indicated that vehicle speed has a significant effect on both the measured dynamic loads and the actual response of the pavement system. However, the effects of vehicle speed on dynamic loads and pavement response are not identical. For example, higher vehicle speed generates higher dynamic loads, whereas the strains at the bottom of the asphalt concrete layer are significantly reduced as the speed increases. This discrepancy has been shown to have a great impact on the final design of the pavement system.

The dynamic interaction that occurs between the loading vehicle and pavement system plays an important role in the development and progression of pavement damage. Both truck dynamics and pavement response characteristics must be considered when determining the extent of the pavement damage and, more importantly, identifying the means by which the pavement damage can be reduced.

Weigh-in-motion (WIM) technology has experienced considerable progress in the past 10 years. Several new WIM systems have been developed with various levels of cost and expected reliability. The main objective of these WIM systems has been to measure the dynamic loads imparted by the vehicle traveling at highway speed. In the process of measuring the dynamic loads, several factors were found to significantly influence the WIM data: degree of road roughness, vehicle speed, load level, and the WIM calibration process. Several studies currently are under way to improve the quality of the WIM data and establish uniform calibration techniques. The study reported in this paper represents an effort to investigate the reliability and repeatability of the WIM data and its correlation to pavement response.

In the case of pavement response characteristics, there are two basic approaches to handling this problem: theoretical modeling and in situ instrumentation. Several computer models are available for computing stresses, strains, and displacements in layered systems. Theoretical pavement responses can be computed if the materials are characterized properly and the loading conditions are well defined. In most cases, material properties are very difficult to define and loading conditions are assumed static for the purpose of simplifying the analysis. In situ instrumentation of pavement systems offers an alternative approach by which the actual pavement responses are measured without making any simplifying assumptions. In this research the strains at the bottom of the asphalt concrete (AC) layer were measured by strain gauges installed in the wheel track of the test section.

OBJECTIVE

The objectives of the research presented in this paper can be summarized as follows:

- To study the effect of vehicle speed on the variability and magnitude of the WIM data,
- To investigate the effect of vehicle speed on the variability and magnitude of tensile strains at the bottom of the AC layer, and
- To investigate any correlations between the effect of vehicle speed on the WIM data and on in situ pavement strain.

PAVEMENT SECTIONS

A flexible pavement section was constructed at the Pennsylvania State University test track. The following table gives the properties of the test section as evaluated from falling weight deflectometer (FWD) testing:

Layer Description	*Thickness (cm)*	*Moduli (MPa)*
AC surface	15	2,550
Crushed aggregate base	20	207
Subgrade	381	152

The variations in axle load, axle configuration, and vehicle speed implemented in this program yielded a wide range of pavement responses and dynamic load magnitudes that provided for an extensive evaluation program.

TESTING PLAN

The objective of this study was to evaluate the variations in the dynamic loads and the strain response at the bottom of the AC layer as a function of speed, axle load level, and axle configuration. Earlier studies have shown that the effect of

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tire pressure on the strains at the bottom of medium to thick AC layers, such as the one evaluated here, is insignificant (*1*). Therefore, only the following test conditions were varied:

- Load level: empty, intermediate, and fully loaded;
- Axle configuration: single-drive axle, front tandem, and back tandem; and
- Testing speed: 32, 56, and 80 km/hr.

Four replicate measurements were collected for each combination of test variables. One full measurement consists of measuring the dynamic loads of the individual axles with one WIM system and the strain response at the bottom of the AC layer with two strain gauges. The two strain gauges were installed at different locations along the longitudinal direction of the test section. The tire pressure remained constant at 861 kPa.

LOAD MEASUREMENT

The WIM system of the Pennsylvania Department of Transportation (PennDOT) was used to evaluate the dynamic load variations at the test sections. This is a Golden River portable system (*2*). The test truck (tractor-trailer combination) was loaded at the three levels—empty, intermediate, and full—and the individual axles were weighed statically and as they ran over the WIM pads. Four replicate measurements were taken for each combination of vehicle speed, axle load, and axle configuration. The WIM system was placed after the test sections to avoid dynamic excitation of the test truck as it approaches the test section. Table 1 gives a summary of the data for the empty load level with the single- and tandem-axle configurations: that, at the speed of 80 km/hr, the dynamic axle load levels deviate the most from the static load levels for all of the axles (i.e., single-axle and front and back tandem axles). Tables 2 and 3 present the data under the intermediate and fully loaded levels, respectively; they show a constant trend where the load on the back tandem axle decreases as the speed increases. Figures 1 through 3 show the relationship between the coefficient of variation and speed for the single-drive and tandem axles, respectively. The data in these figures indicate that the variability of the dynamic loads at the empty load level is highly dependent on the speed. At the intermediate and full load levels, the effect of speed is insignificant except in the back tandem axle case (Figure 3).

The difference between the static and dynamic loads is another important factor when considering pavement loading. The majority of the pavement design and analysis procedures consider static loads. Therefore, the differences between static and dynamic loads would indicate how conservative or nonconservative these assumptions are. In this analysis, the difference between static and dynamic loads is calculated as the mean of dynamic loads at a given speed minus the static load. Figures 4 through 6 show the difference between static and dynamic load data as a function of vehicle speed for all three axles. The differences are expressed in arithmetic values instead of absolute values to differentiate among the cases in which the dynamic loads are higher or lower than the static load.

The data in Figures 4 through 6 indicate that, in the majority of cases (17 out of 27 combinations), the dynamic loads are higher than the static loads (i.e., a positive difference). It is

TABLE 1 Dynamic Loads from Single-Drive and Tandem Axles for Empty Load Level

	Speed (km/h)	Single Axle Drive	Front Tandem	Back Tandem
	0	40	14	15
	32	44	25	23
	32	42	25	23
	32	44	25	23
	32	38	26	22
Mean		42	25	23
STD		2.6	0.5	0.5
CV (%)		6	2	2
	56	40	22	22
	56	49	26	22
	56	49	30	24
	56	43	23	21
Mean		45	25	22
STD		4	3	1
CV (%)		9	12	5
	80	46	34	30
	80	48	43	31
	80	46	41	25
	80	66	48	30
Mean		52	42	29
STD		10	12	3
CV (%)		19	29	10

TABLE 2 Dynamic Loads from Single-Drive and Tandem Axles for Intermediate Load Level

	Speed (km/h)	Single Axle Drive	Front Tandem	Back Tandem
	0	59	61	45
	32	53	43	57
	32	52	44	52
	32	53	45	57
	32	53	43	55
Mean		53	44	55
STD		0.5	1	2
CV (%)		1	2	4
	56	55	50	47
	56	63	59	43
	56	59	55	45
	56	61	56	37
Mean		59	55	43
STD		3	4	4
CV (%)		5	7	9
	80	69	71	46
	80	64	64	34
	80	67	69	33
	80	68	68	33
Mean		67	68	36
STD		2	3	6
CV (%)		3	4	17

TABLE 3 Dynamic Loads from Single-Drive and Tandem Axles for Fully Loaded Level

	Speed (km/h)	Single Axle Drive	Front Tandem	Back Tandem
	0	81	103	78
	32	71	81	76
	32	75	89	78
	32	70	83	77
	32	75	87	77
Mean		73	85	77
STD		2	3	1
CV (%)		3	4	1
	56	80	93	88
	56	80	92	90
	56	84	91	91
	56	80	90	88
Mean		81	91	89
STD		2	2	1
CV (%)		2	2	1
	80	87	82	79
	80	88	83	78
	80	92	89	86
	80	86	84	82
Mean		88	85	81
STD		2	3	4
CV (%)		2	4	5

also seen that, at the empty load level, the dynamic loads are always higher than the static values. In the intermediate and fully loaded cases, the differences are evenly distributed between negatives and positives. This distribution indicates that, at the empty load level, the test truck is experiencing a higher dynamic effect than at the other two load levels.

STRAIN MEASUREMENT

This testing program was conducted on an instrumented flexible pavement test section with the properties shown earlier. The instrumentation of the test section consisted of strain gauges at the bottom of the AC layer in the longitudinal direction. The gauges were located in the outer wheel track at various stations throughout the sections. The strain gauges were of the *H*-gauge type, which are installed during the construction of the test section (Figure 7).

The data analyzed in this paper were collected from strain gauges located at Stations 10 and 29. The station number indicates the distance in feet from the beginning of the section. Table 4 gives the strain measurements under the single-drive axle and 861 kPa of tire pressure. In the case of a tandem axle, unlike the WIM data, only the strain values under the back tandem axle were extracted from the actual measurement. The data indicated that the maximum tensile strain at the bottom of the AC layer always occurred under the back tandem axle (*3*). Table 5 summarizes the strain data under the back tandem axle.

It is well known that the strains at the bottom of the AC layer are highly sensitive to the pavement temperature at the time of testing. In this study, the pavement temperature was

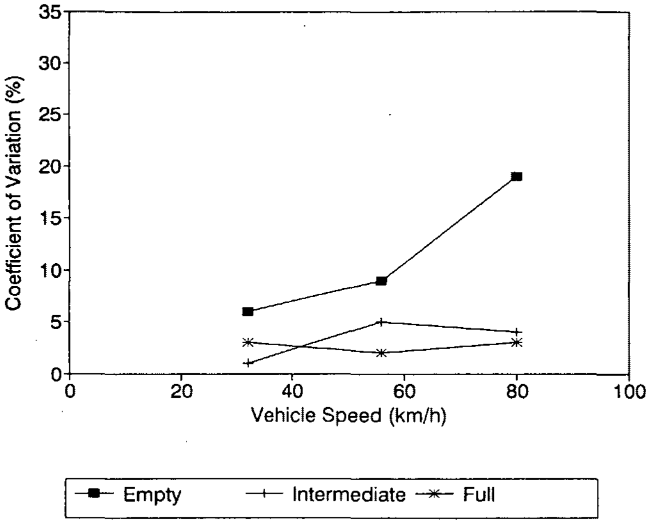

FIGURE 1 Effect of vehicle speed on variability of dynamic loads, single-drive axle.

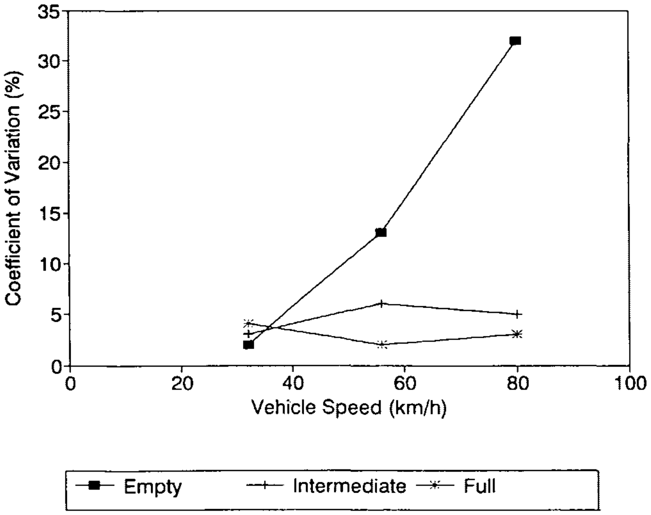

FIGURE 2 Effect of vehicle speed on variability of dynamic loads, front tandem axle.

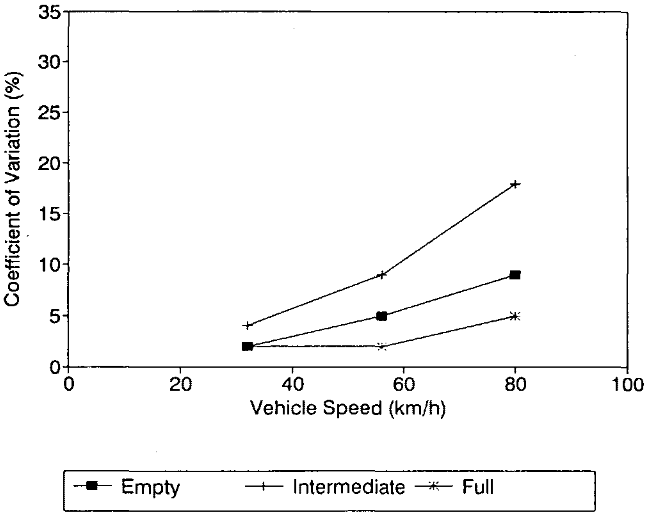

FIGURE 3 Effect of vehicle speed on variability of dynamic loads, back tandem axle.

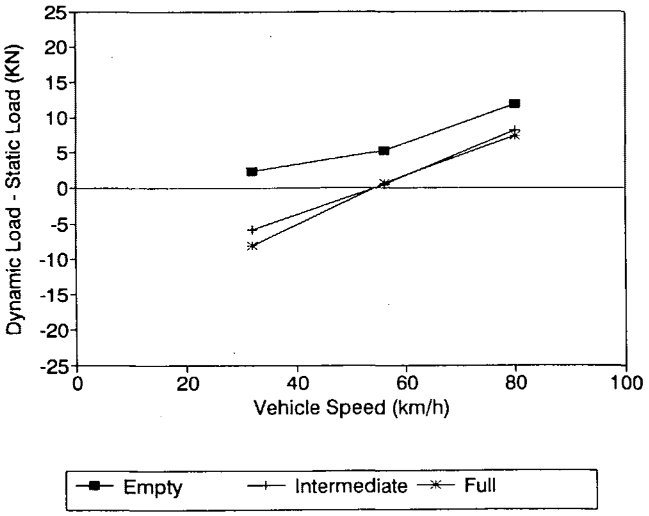

FIGURE 4 Effect of vehicle speed on difference between dynamic and static loads, single-drive axle.

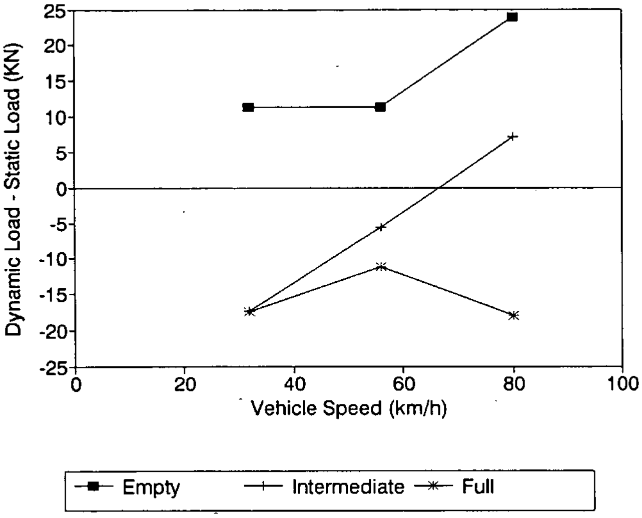

FIGURE 5 Effect of vehicle speed on difference between dynamic and static loads, front tandem axle.

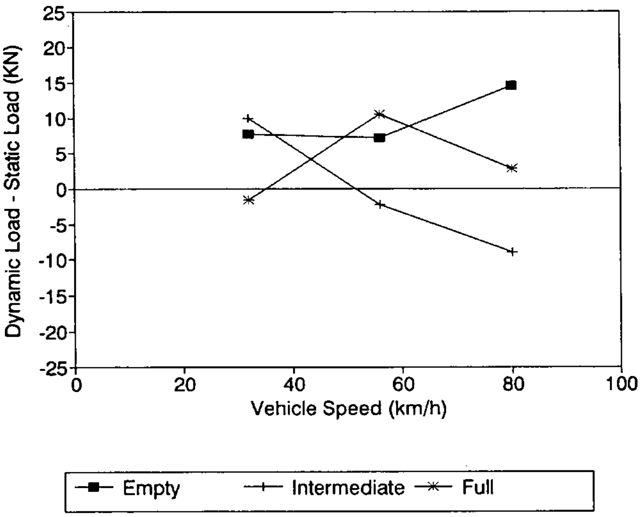

FIGURE 6 Effect of vehicle speed on difference between dynamic and static loads, back tandem axle.

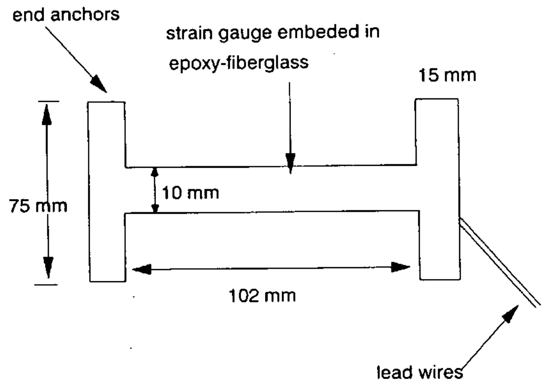

FIGURE 7 Typical *H*-type strain gauge.

measured throughout the various layers. However, for the data analysis presented in this paper, the temperature effect is insignificant because the various replicate measurements at all three speeds were collected within 15 min. Average pavement temperature is not expected to vary significantly within 15 min; therefore, no temperature adjustment was necessary. The effect of the transverse location of the truck relative to the strain gauges was handled by using an ultrasonic distance-measuring device and accepting only the replicates that were within 2.5 cm of each other.

The analysis of the strain data follows the same procedure as that for the WIM data. Because the two strain gauges are located at different stations, the effect of vehicle speed on the strains at various locations can also be compared. The data in Tables 4 and 5 indicate that the effect of speed on the variability of strain is insignificant. However, the truck speed has a tremendous effect on the magnitude of the measured strain. Figure 8 shows the relationship between the strains at Station 10 and the vehicle speed for all load levels. By varying the speed from 32 to 80 km/hr, the strains are reduced by 50 percent in almost all cases. Theoretically, the effect of the viscoelasticity of the AC layer can be the reason for this large reduction in the strains. Because of the viscoelastic nature of the AC material, the material will show stiffer behavior under shorter loading times. The shorter loading times occur at higher speeds, which explains the observed large reductions in the strains under higher speeds.

Another way to assess the effect of vehicle dynamics on pavement loading is to compare the measured strains at the two locations as a function of speed for all load levels. For this analysis, the nonuniformity of the pavement material between the two stations must be taken into account. For this purpose, FWD testing was conducted at both stations, and the layer moduli were backcalculated. This analysis indicates that the difference between the material properties at the two stations is very small and would have an insignificant effect on the strains. Figure 9 shows the percent difference in strains as a function of vehicle speeds for the intermediate and full load levels. The data from the empty load level were inconsistent. The data in Figure 9 indicate that the strains at various locations in the section are highly dependent on the speed. However, the major significance of the speed occurs between 32 and 56 km/hr. These data clearly indicate the significance of truck dynamics on the response of the pavement.

EFFECT OF VEHICLE SPEED ON PAVEMENT LOADS AND PAVEMENT RESPONSE

This analysis will investigate the possibility of relating the effect of speed on both the loads and the strains. Because they represent the pavement response, the strains should be directly influenced by the magnitude of the applied load. However, strains in the AC layer are highly dependent on the properties of the material. Therefore, the thought relationship may not be easily found, especially because AC material is viscoelastic in nature.

The load and strain (Station 10) data under the single-drive axle are analyzed in this section. The objective here is to prove whether there is any correlation between the effect of speed on load and strain. Load levels were measured at 0, 32, 56, and 80 km/hr, whereas strains were measured only

TABLE 4 Longitudinal Strains at Bottom of AC Layer with Single-Drive Axle and 125-psi Tire Pressure

		LOAD LEVEL					
	Speed	Empty		Intermediate		Full	
		Sta 10	Sta 29	Sta 10	Sta 29	Sta 10	Sta 29
	32	74	115	148	159	284	354
	32	83	118	153	174	319	368
	32	81	130	158	174	357	392
	32	84	118	140	159	315	373
Mean		81	120	150	166	319	372
STD		4	6	7	7	26	13
CV (%)		5	5	4	4	8	4
	56	73	73	102	137	218	283
	56	80	78	91	130	218	278
	56	78	83	98	130	220	280
	56	77	83	99	132	220	282
Mean		77	80	98	132	219	280
STD		3	4	4	3	1	1
CV (%)		4	5	4	2	1	1
	80	58	69	60	81	127	166
	80	60	69	61	83	136	169
	80	56	66	60	81	136	179
	80	53	64	60	88	145	179
Mean		57	67	61	83	136	173
STD		3	2	1	3	6	6
CV (%)		4	3	1	4	5	3

TABLE 5 Longitudinal Strains at Bottom of AC Layer with Tandem Axle and 125-psi Tire Pressure

		LOAD LEVEL					
	Speed	Empty		Intermediate		Full	
		Sta 10	Sta 29	Sta 10	Sta 29	Sta 10	Sta 29
	32	34	56	133	142	292	338
	32	43	56	133	135	283	311
	32	39	64	132	154	272	336
	32	42	59	127	140	280	299
Mean		40	59	131	143	282	321
STD		4	3	2	7	8	17
CV (%)		10	5	2	5	3	5
	56	17	27	98	118	186	239
	56	18	25	94	118	188	249
	56	18	27	91	122	179	234
	56	17	25	94	118	185	238
Mean		18	26	94	119	185	240
STD		1	1	3	2	4	5
CV (%)		4	5	3	2	2	2
	80	22	17	66	88	80	122
	80	24	20	66	91	85	125
	80	20	20	74	91	84	130
	80	21	17	73	93	98	135
Mean		22	18	70	91	87	128
STD		2	1	4	2	8	5
CV (%)		7	7	6	2	9	4

under speeds of 32, 56, and 80 km/hr. Therefore, the 32-km/hr speed is used as the base level for both load and strain data. At each speed level, the percentage of difference is evaluated for both the load and the strain. The percentage of difference is defined as the difference between the measurement (i.e., load or strain) at any speed minus the measurement at 32 km/hr divided by the measurement at 32 km/hr multiplied by 100.

Figure 10 represents the effect of speed on the measured load and strain. The figure shows that the speed has a significant effect on both the load and the strain. However, the two effects are reversed. In the case of load, the higher the speed, the larger the measured load; whereas, in the case of strain, the higher the speed, the lower the measured strain. This indicates that, even though a vehicle speed increase, vehicle dynamics, and, therefore, higher dynamic loads are generated, the viscoelastic behavior of AC materials greatly outweighs this effect.

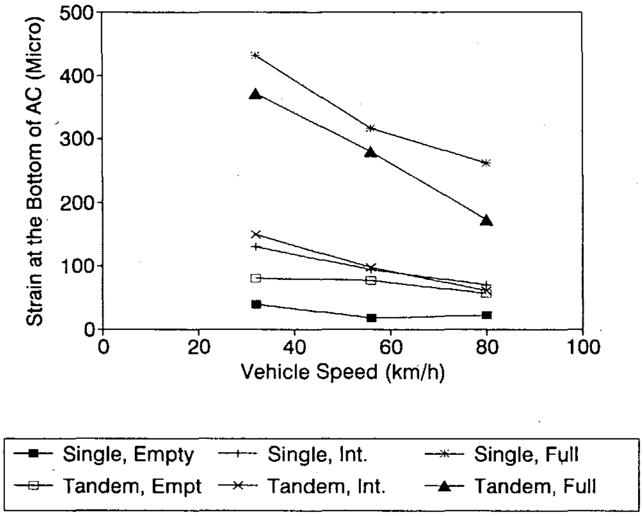

FIGURE 8 Effect of vehicle speed on tensile strain at bottom of AC layer.

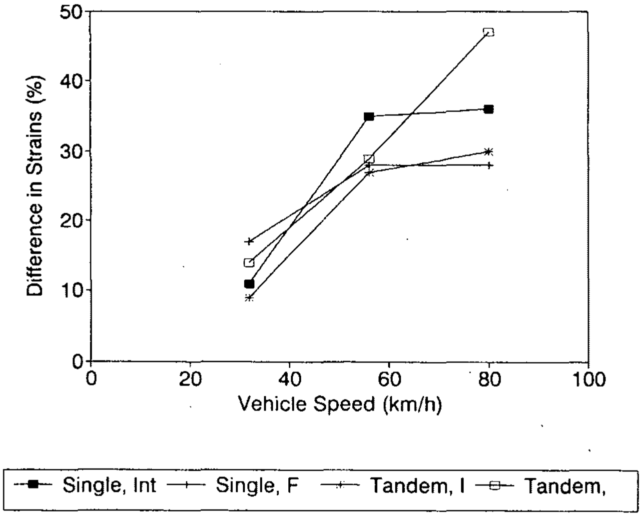

FIGURE 9 Effect of vehicle speed on strains at various locations within test sections.

EFFECT OF FACTORS ON PAVEMENT DESIGN

The objective of this analysis is to evaluate the effect of the various factors on pavement design and analysis. First, it is necessary to define the uses of the WIM load data and the strain data in the pavement design process. The WIM load data are widely used to predict the 80-kN equivalent single-axle loads (ESALs) generated by the passage of the weighted axle. These ESALs are generated on the basis of the AASHTO load equivalency factors (LEF) (*4*). The strain data can also be used to predict ESALs that are based on a mechanistic fatigue criterion, such as the one recommended by Finn et al. (*5*).

$$N_f = 15.947 - 3.291 \log(\varepsilon) - 0.854 \log\left(\frac{E}{103}\right) \qquad (1)$$

where:

N_f = number of ESALs needed to cause fatigue failure,
ε = tensile strain at bottom of AC layer (microstrain), and
E = modulus of AC layer.

Therefore, by using the WIM load data and the strain data, two types of LEFs, one using the AASHTO approach and one using the fatigue criterion, can be evaluated. The fully loaded case of the single-drive axle had a mean value of 81 kN at 56 km/hr (Table 3), which is very close to 80 kN. Therefore, the fully loaded case of the single-drive axle at 56 km/hr is considered the standard axle load. To obtain AASHTO LEFs on the basis of the WIM data, the structural number (SN) and the terminal serviceability of the test section are needed. The SN is evaluated as follows:

$$SN = \Sigma a_i D_i \qquad (2)$$

where D_i is thickness of layer i and a_i is layer coefficient for layer i. In this case, the SN is calculated to be 4.0 and the

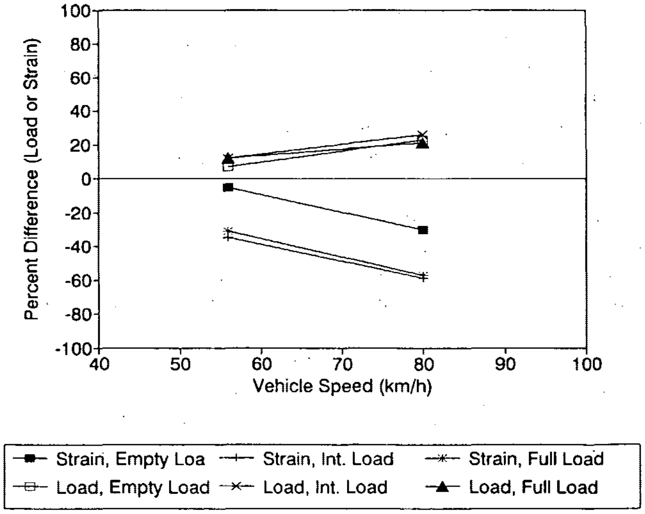

FIGURE 10 Comparison between effect of vehicle speed on dynamic loads and strains.

terminal serviceability index (PSI) is assumed to be 3.0. Using the *SN* of 4.0 and terminal PSI of 3.0, AASHTO LEFs for the single-drive axle were obtained:

Speed (km/hr)	*Load Level*		
	Empty	*Intermediate*	*Full*
32	0.11	0.254	0.74
56	0.14	0.39	1.00
80	0.23	0.58	1.34

The LEFs based on the fatigue failure criterion were evaluated as follows:

- Assume that the intermediate load test at 56 km/hr is the standard load.
- Use the strain values from Table 4 and the AC moduli given earlier in the fatigue failure criterion to evaluate the N_f for each combination of speed and load level.
- Finally, evaluate the LEF as the ratio of the N_f at any combination of speed and load level to the N_f value at the 35-km/hr speed and intermediate load level.

The following table summarizes the values of the LEFs for the single-drive axle on the basis of the fatigue failure criterion:

Speed (km/hr)	*Load Level*		
	Empty	*Intermediate*	*Full*
32	0.04	0.29	3.44
56	0.03	0.07	1.00
80	0.01	0.02	0.21

A comparison of the data in the preceding tables indicates that there are significant differences between the two types of LEFs. The WIM data indicate that the LEFs increase as the speed increases, whereas the strain data indicate the opposite. As a result of this contradiction, major differences can be expected in designing pavement structures on the basis of the AASHTO design guide or the mechanistic approach.

SUMMARY AND CONCLUSIONS

In this paper, the effect of vehicle speed on both the measured load and pavement strain response has been analyzed. The WIM technology was used to measure the dynamic loads imparted by the moving vehicle. The pavement strain response under dynamic loads was measured by strain gauges embedded into the AC layer. On the basis of the analysis of the data, the following conclusions can be drawn.

- The WIM data indicate that in the majority of the cases the dynamic loads are higher than the static loads. It was also shown that at the empty load level, the truck would experience a higher dynamic effect than at the intermediate and full load levels.
- The variability of the dynamic loads at the empty load level (i.e., coefficient of variation of four replicates) is highly dependent on the speed. At the intermediate and full load levels, the WIM measurements were more repeatable at various speeds.
- The strain data indicate that the speed has a significant effect on the strain response of flexible pavement. By increasing the speed from 32 to 56 km/hr, the tensile strains at the bottom of the AC layer are reduced by 50 percent.
- The strain data indicate that the strain response at various locations of the road is highly dependent on the vehicle speed. However, the major significance of the speed occurs between 32 and 56 km/hr. Both the WIM and strain data indicated that the effect of vehicle dynamic are more significant at the empty load level.
- The LEFs analysis revealed very interesting facts about the discrepancies between using the WIM data and the use of the mechanistic approach. This contradiction between the two approaches has a great impact on the current practice in pavement design and analysis. Currently the majority of highway agencies follows the AASHTO design guide for the design of new pavement, whereas overlays are being designed by either an empirical approach or a mechanistic analysis. The data given in the preceding tables indicate that by using the WIM data and the AASHTO LEFs, a very conservative estimate of ESAL is obtained compared with the fatigue failure criterion approach. For mechanistic overlay analyses, there is an even more serious problem. The majority of the mechanistic overlay design procedures currently used by highway agencies are based on theoretical analysis by which the strains are evaluated. The computed strains are then used in a fatigue failure criterion to predict the pavement life. Finally, the predicted pavement life in terms of the number of ESALs is compared with the expected ESALs obtained from WIM data or other traffic analyses. This analysis process contains two contradictory approaches that should not be combined because of their inconsistencies.
- Finally, on the basis of the analysis presented in this paper, it is evident that more rational pavement analysis models should be investigated. The ideal pavement analysis model should consider the dynamic nature of traffic loads and the viscoelastic properties of the AC material. In addition, the current practice of using the WIM data with both new design and overlay design procedures must be seriously investigated.

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