PAVEMENT DAMAGE FROM TRANSIT BUSES AND MOTOR COACHES

Edward Fekpe, PhD PEng MASCE
Energy, Transportation, and Environment Division
Battelle Memorial Institute
505 King Avenue, Columbus, OH 43201
Tel. 614-424-5343; Fax. 614-458-5343
E-mail: fekpee@battelle.org

ABSTRACT

This paper investigates the load-associated pavement damage effects of transit and intercity (motor coaches) buses operating on urban and rural interstate highway systems. The paper presents analyses of (i) the effect of pavement surface roughness on pavement damage potential from transit and intercity buses with different lengths, (ii) the effects of changes in the weights of transit buses on pavement damage potential, and (iii) pavement damage from transit buses and motor coaches compared to the five-axle tractor semitrailer truck (3-S2). Pavement damage is calculated based on the dynamic axle loads where the static weights are corrected for the dynamic effects of moving loads. Pavement damage generally increases with pavement surface roughness and vehicle speed. For very good pavements, the effect of vehicle speed on pavement damage is negligible. Vehicles potentially impose higher distresses on pavements in fair condition when driven at relatively high speeds. In terms of total pavement damage on interstate highways, the 30-ft transit bus causes 9 to 12 percent of the damage caused by the 3-S2 reference truck, while the 40-ft transit bus causes 14 to 19 percent.

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1 INTRODUCTION

It is widely understood that trucks, especially overweight trucks, contribute significantly to highway pavement damage. It is known that fully loaded transit buses and motor coaches often exceed the maximum permissible axle weights. However, the extent of damage caused by overweight transit buses and motor coaches has not been extensively investigated. Transit buses refer to urban commuter buses and motor coaches refer to intercity buses.

The direct influence of buses and motor coaches on pavements and the effects of dynamic load transfer are important elements in evaluating the impacts of bus operations on highway pavements. In urban areas, pavement deterioration and mostly rutting in bus bays and curb lanes has been identified as a high cost maintenance problem. Repeated passages of vehicles on pavements eventually results in certain types of distresses: fatigue cracking, rutting, and roughness. The primary objective of this research was to estimate the pavement damage potential of transit and intercity (motor coaches) buses on urban and rural interstate highway systems. The parameter most widely used for analyzing pavement damage is the equivalent standard axle load (ESAL) weighted by some measure of facility usage such as average annual vehicle miles traveled (VMT).

This paper investigates the load-associated pavement damage effects of different types of buses and motor coaches operating on urban and rural interstate highway systems. This paper also presents analyses of (i) the effect of pavement surface roughness on pavement damage potential from transit and intercity buses with different lengths, (ii) the effects of changes in the weights of transit buses on pavement damage potential, and (iii) the pavement damage potential of transit buses and coach relative to the five-axle tractor semitrailer truck (3-S2). This truck is used as a reference to gauge the relative potential pavement damage.

2 ANALYTICAL FRAMEWORK

The magnitude of loads imposed on the pavement is determined by the configuration of the axle units on the vehicle, payload, suspensions systems, size, type, and pressure of tires. Recent research in vehicle-pavement interaction includes the measurement of dynamic wheel loads (DWL) and analysis of the potential pavement damage from heavy vehicles. The magnitude and variation of dynamic wheel loads is dependent on both vehicle and pavement characteristics. On the vehicle side, the load transmitting mechanism, particularly the suspension systems, speed of travel, and the weight of payload are contributing variables. On the pavement structure side, surface roughness is the characteristic that determines the resulting dynamic wheel load.

Dynamic Load Coefficient (DLC) is a measure that indicates the variation of the wheel forces experienced by the pavement and a reflection of the DWL. Dynamic wheel load may be defined as the actual load impact experienced by the pavement structure under the action of a moving vehicle wheel. DLC, by definition, is a statistical coefficient of variation of the wheel forces along a given pavement section and therefore indicates how the wheel forces vary along that section. Therefore, in calculating the pavement damage resulting from dynamic wheel loads, the static axle load is corrected for its dynamic component generated by being in motion. This approach is appealing because the dynamic component can be directly related to a parameter that reflects the condition of the pavement (i.e., road roughness).

A statistical relationship between DWL and pavement surface roughness was used (Fekpe, 1999) to correct for the dynamic component in the ESAL calculations. The parametric form of the model is shown in Eqns. 1 and 2.

$$DLC = A(v).IRI^{n} \qquad (1)$$

$$A(v) = (\kappa + \gamma.V) / 1000 \qquad (2)$$

where:

DLC – dynamic load coefficient;
IRI – international roughness index (m/km);
A(v) – coefficient, function of vehicle speed;
n – exponent, depends on axle and suspension type;
V – speed in kph; and
κ, γ – constants.

The procedure for correcting for the dynamic component in the static moving load is illustrated in Eqns. 3 to 6. For the purposes of this analysis, one increment above the mean value (or mean static moving wheel load) in terms of the standard deviation was considered, i.e., $\lambda = 1.0$.

$$DLC = \sigma / X = f(IRI, v) \qquad (3)$$

$$WL_m = SWL + \lambda \cdot \sigma \qquad (4)$$

$$WL_m = SWL\,(1 + \lambda \cdot DLC) \qquad (5)$$

$$WL_m = SWL\,[1 + \lambda \cdot A(v) \cdot IRI^{n}] \qquad (6)$$

where:
WLm – corrected wheel load;
SWL – average static wheel load; and
λ – multiplier (1.0 to 2.0 recommended, depending on roughness).

The traffic-induced pavement deterioration effects were analyzed for each bus type and by functional highway class. Pavement damage was estimated in terms of the equivalent standard axle load (ESAL) and weighted by a measure of facility usage i.e., vehicle miles of travel (VMT). The corrected wheel loads were used to estimate ESALs.

Computer simulations were used to generate the DLC and standard deviations of the wheel load variations of 30-ft and 40-ft transit buses and 5-axle tractor semi trailer truck with different axle weights operating at different speeds on three types of pavement roughness. The gross vehicles weight (GVW) of the 30-ft bus was 31,200 lbs, while the GVW for the 40-ft bus ranges from 30,500 lbs to 46,800 lbs. GVW for the 3-S2 truck was 80,000 lbs. The measurements were made at 10, 30, 50, 70, 90, and 110 kph speeds respectively. The three types of pavements simulated were classified as: (i) very good, IRI value of 50 in/mile; (ii) good, IRI value of 100 in/mile; and (iii) fair, IRI value of 170 in/mile. Figure 1 shows the profiles of the pavements simulated. The combined range of roughness is believed to be representative of the practical spectrum of roughness of typical roads that the buses and trucks investigated would traverse. The buses and truck were assumed to be equipped with air suspensions systems. The following sections discuss the results of the analyses.

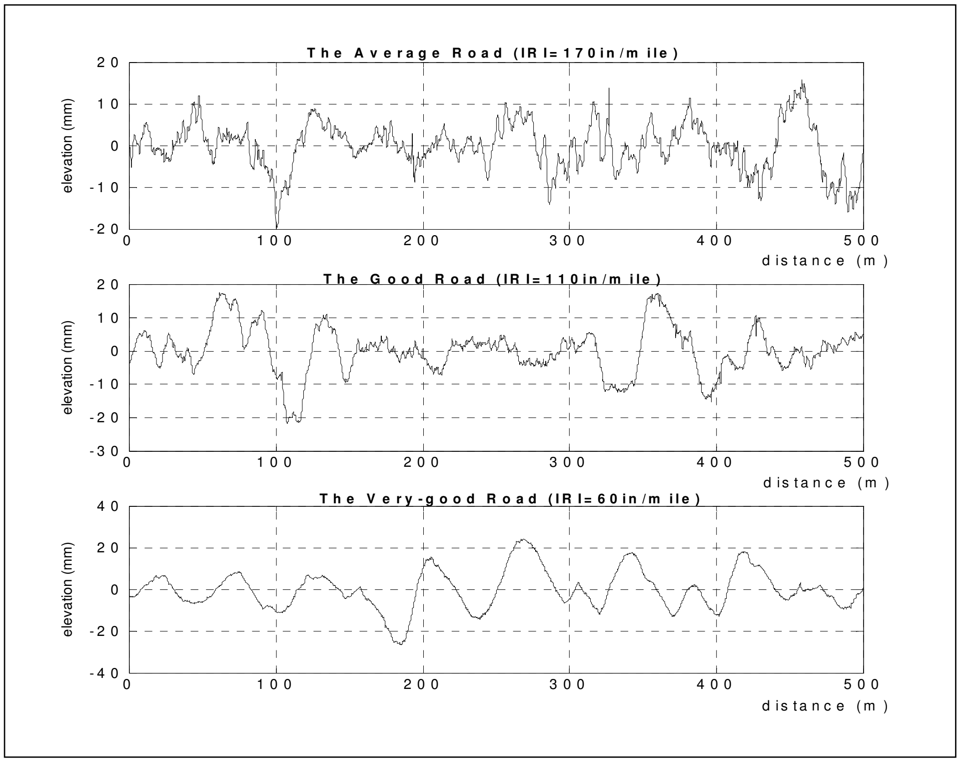

Figure 1. Road Profiles (Kulakowski et al, 2002)

3 DAMAGE PER VEHICLE

As noted in the introduction, the first part of the analysis examined the effects of pavement surface roughness on potential pavement damage imposed by 30-ft and 40-ft transit buses and 45-ft motor coaches at various operating speeds. Table 1 and Figure 2 show the relationships between ESAL per vehicle and speed of travel for the three levels of pavement surface roughness.

It is noted that the ESAL generally increases with roughness and speed. However, ESAL appears to stabilize at speeds above 90-km/hr or 56-mph. The variation of pavement damage with pavement surface roughness is identical for the transit buses and motor coach. ESAL for the 30-ft transit bus operating on a very good pavement surface ranges from 2.40 at the speed of

10-km/hr to 2.55 at the speed of 110-km/hr with an average of 2.48. The average ESALs per vehicle for the good and fair pavements are 2.60 and 2.73 respectively. For the 30-ft transit bus operating on a very good pavement surface, ESAL increases at a rate of 1.5 percent for every 10-km/hr increase in speed. For good pavement surface, the rate of increase is 3.3 percent and for a fair pavement surface the rate is 4.9 percent per 10-km/hr increase in speed. Similar values were observed for the motor coach. For the 40-ft transit bus however, the rate of increase are on 3.0 percent for very good pavement surface; 4.8 percent for good pavement and 7.2 percent per 10-km/hr increase in speed.

Table 1. Effect of roughness and speed on ESAL

Vehicle	Roughness (in./mile)	ESAL/vehicle					
		10 km/hr	30 km/hr	50 km/hr	70 km/hr	90 km/hr	110 km/hr
30-ft Transit Bus (GVW = 31,200 lbs)	60	2.403	2.437	2.460	2.490	2.558	2.545
	110	2.427	2.496	2.538	2.659	2.759	2.719
	170	2.432	2.561	2.688	2.913	2.927	2.848
40 ft. Transit Bus (GVW = 38,100 lbs)	60	3.852	3.919	3.975	3.987	4.150	4.091
	110	3.899	4.044	4.093	4.277	4.383	4.501
	170	3.918	4.248	4.327	4.379	4.640	4.547
45 ft. Motor Coach GVW = 44,400 lbs)	60	2.490	2.505	2.532	2.549	2.578	2.614
	110	2.523	2.567	2.625	2.798	2.672	2.791
	170	2.554	2.646	2.815	3.046	2.833	2.955
5-axle Tractor Semitrailer (GVW = 80,000 lbs)	60	2.565	2.576	2.583	2.604	2.631	2.635
	110	2.576	2.608	2.625	2.655	2.837	2.838
	170	2.600	2.651	2.670	2.716	2.846	2.802

These results indicate that ESAL is more sensitive to speed on fair pavement surfaces than on smooth (or very good) pavement surfaces. This implies that vehicles potentially impose higher distresses on fair pavement when driven at relatively high speeds. Also, the potential pavement damage from a 40-ft transit bus on a given pavement surface, is between 58 and 62 percent higher than the impact of a 30-ft transit bus driven at the same speed. The rougher the pavement the greater the difference. While it is observed in Table 1 and Figure 2 that ESAL increases with pavement surface roughness, the effect of roughness on ESAL is greatest when the pavement surface deteriorates to a point where it can be classified as being in a fair condition. Thus, in order to minimize or reduce the potential pavement damage from vehicle operations, it would be advisable to follow a structured maintenance program that ensures that the pavement surfaces are kept in very good or fair conditions at all times.

It is interesting to note in Figure 2 that ESAL drops after a certain speed, particularly on fair and rough pavement surfaces. This can be explained in part by the fact that the dynamic wheel load is a power function of speed. This implies that there is a turning point at which ESAL would begin to decrease with increasing speed.

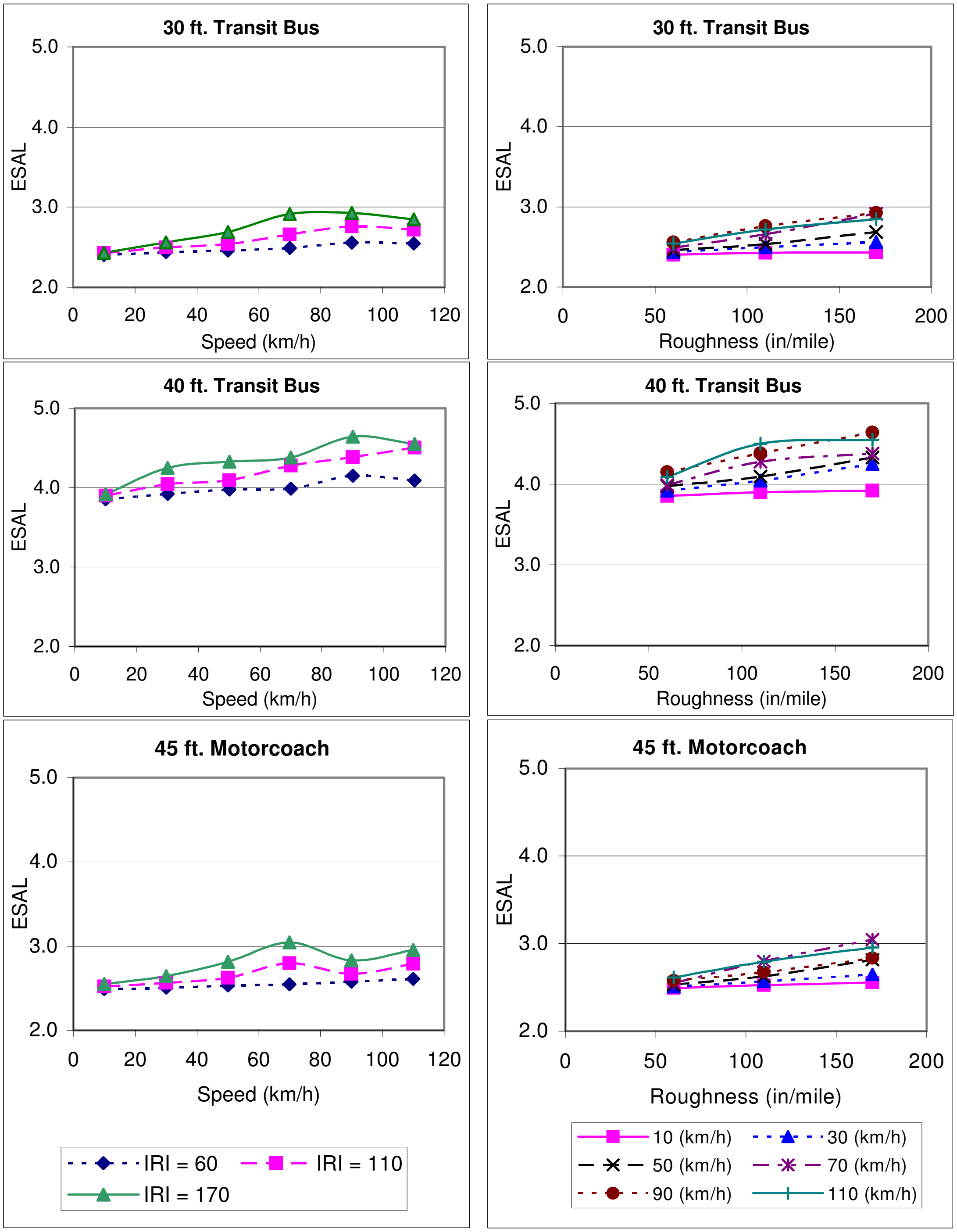

Figure 2. ESAL per Vehicle by Speed of Travel

4 EFFECT OF DIFFERENCES IN BUS WEIGHT

Differences in bus weight could be the result of major component improvements, addition of components to satisfy requirements such as the Clean Air Act or the Americans with Disabilities Act of 1990, or to meet future design standards. It has been observed that chassis engine and axle groups represent the most important share of a transit bus' weight (Corbeil et al., 1995).

Thus a small change in one of these components might result in a substantial weight impact, either increasing or reducing bus weight. Features such as air conditioning, wheelchair lifts, and CNG tanks add substantial weight to buses. Also, bus weight could be increased due to requirements of crashworthiness and long life. Even though the specific weight of each of these components is not known, buses equipped with such features are heavier than the average standard transit buses.

Due to limited data, weight increases due to the addition of specific components in compliance with regulatory requirements could not be estimated directly in this research. The second part of the analysis was intended to illustrate the effect of new technologies that might result in changes in bus weight on pavement damage. Three GVWs of the standard 40-ft transit bus (i.e., 30,500-lbs, 38,100-lbs and 46,800-lbs) on pavement roughness of 160-in/mile were used for this analysis. This roughness was used to reflect the worst-case scenario. The range of bus weights was assumed to cover the possible weight spectrum of standard transit buses that might result from component changes. For example, the light bus (i.e., 30,500-lbs) depicts the use of lightweight material in bus manufacture while the heavy bus (i.e., 46,800-lbs) depicts the situation where the addition of components results in weight increases.

Table 2 summarizes the ESAL values for each vehicle. The average ESAL for the light bus (i.e., GVW of 30,500-lbs) is 1.87 and the average ESAL for the medium weight is 4.38, which is about 2.3 times that of light bus and about 50 percent of the average ESAL for the heavy bus. Obviously, the potential pavement damage increases exponentially with increases in bus weight. Technologies that reduce bus weight are obviously beneficial to pavement life, as opposed to technologies that increase bus weight.

Table 2. ESALs and relative ESAL by GVW

GVW (lbs)	10 km/hr	30 km/hr	50 km/hr	70 km/hr	90 km/hr	110 km/hr
ESAL per Vehicle						
30,460	1.669	1.778	1.899	1.890	2.015	1.984
38,210	3.955	4.288	4.368	4.420	4.682	4.588
45,780	7.830	8.460	8.519	9.074	9.191	8.958
Relative ESAL						
30,460	0.642	0.671	0.711	0.696	0.708	0.708
38,210	1.521	1.617	1.636	1.627	1.645	1.637
45,780	3.011	3.191	3.190	3.341	3.230	3.197

It is recognized that not all transit buses are or will be equipped with one or more of the features and technologies at any given time. It is also important to note that the analysis was conducted for the worst type of pavement surface simulated. Therefore, the potential damage on very good pavements would be less i.e., at least 10 percent less than that on fair pavements.

5 COMPARISON OF ESAL FOR BUSES WITH 3-S2 TRUCK

In analyzing the relative pavement impacts of the transit buses and motor coach to the 3-S2 truck, the ESALs for the buses were expressed as fractions of the truck. The results are summarized in Table 3. Figure 3 clearly shows that the ESAL values for the 30-ft transit bus and the motor coach are similar to those of the 3-S2 truck for all pavement surface roughness and speeds.

Table 3. Relative ESAL by roughness and speed

Vehicle	Roughness (in/mile)	Relative ESAL					
		10 km/hr	**30** km/hr	**50** km/hr	**70** km/hr	**90** km/hr	110 km/hr
30-ft Transit Bus (GVW=31,200-lbs)	60	0.937	0.946	0.952	0.956	0.972	0.966
	110	0.942	0.957	0.967	1.002	0.972	0.958
	170	0.935	0.966	1.007	1.072	1.029	1.016
40-ft Transit Bus (GVW=38,100-lbs)	60	1.502	1.522	1.539	1.531	1.577	1.553
	110	1.514	1.550	1.559	1.611	1.545	1.586
	170	1.507	1.602	1.621	1.612	1.630	1.623
45-ft Motor Coach (GVW=44,400-lbs)	60	0.971	0.972	0.980	0.979	0.980	0.992
	110	0.980	0.984	1.000	1.054	0.942	0.984
	170	0.982	0.998	1.054	1.122	0.995	1.054

Note that the ESAL of the 30-ft bus is around 0.9 to 1.1 times that of the 3-S2 truck. The corresponding ratios for the motor coach are 1.09 to 1.08. These values clearly indicate that the 30-ft transit bus, motor coach, and 3-S2 truck cause comparable amounts of pavement damage when operated at similar speeds and on identical pavement surfaces. The 40-ft transit bus on the other hand, causes about 1.6 times the potential pavement damage imposed by the 3-S2 truck operating at similar speed on identical pavement surfaces. The heavier and longer 40-ft transit buses with single axle configuration impose potentially higher pavement damage

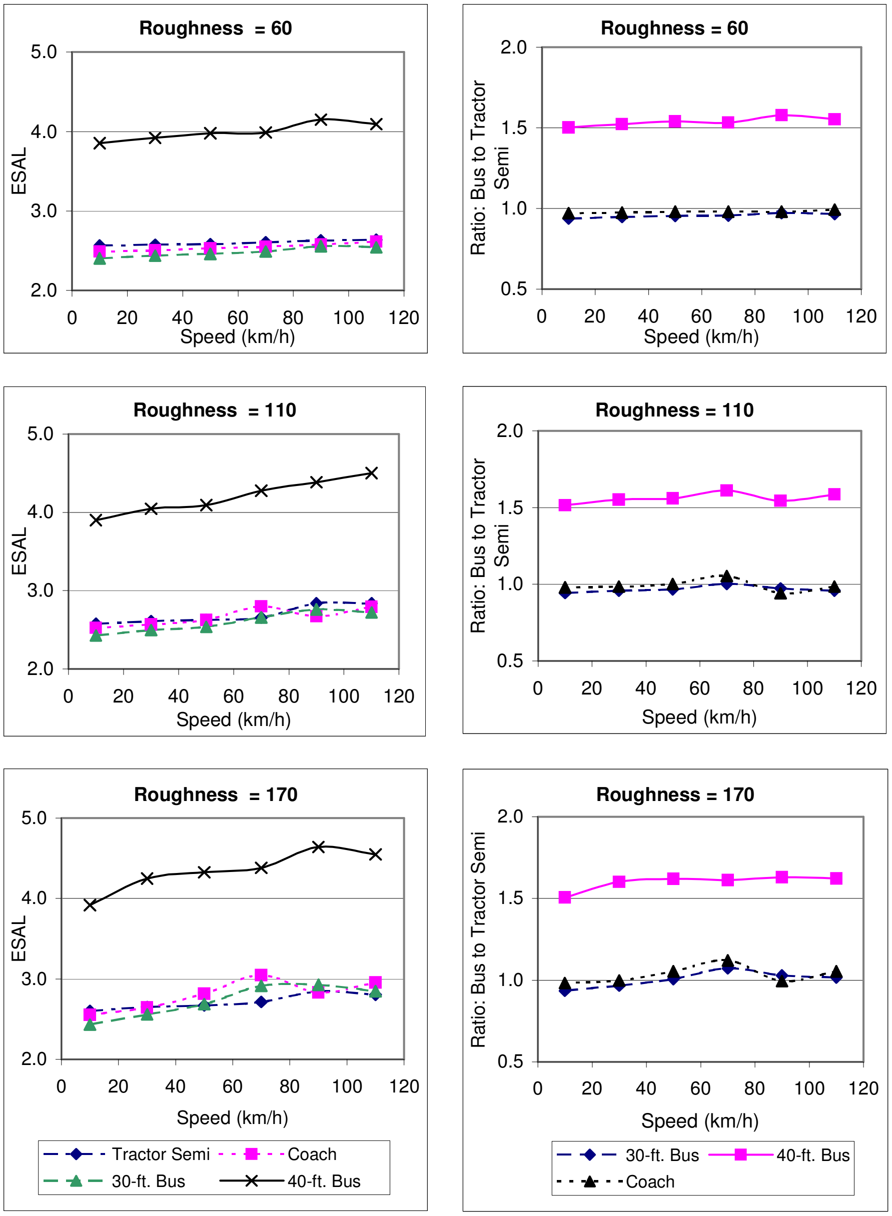

Figure 3. Comparison of Bus and Motor Coach ESALs to 3-S2 Truck

6 TOTAL PAVEMENT DAMAGE (ESAL-VMT)

In order to assess the total pavement damage associated with each vehicle type operating on the highway system, the damage per vehicle was weighted by a measure of facility usage i.e., VMT. ESAL-VMT is used as an indication of total load repetitions imposed by each vehicle type. It was noted that highway cost allocation and road use charges or taxes are usually based on ESAL-VMT (Fekpe, et al., 1995).

The ranges of the ESAL-VMT for speeds from 10 to 110-km/hr for each vehicle are summarized in Table 4. The results for each bus type were also compared to the reference 3-S2 truck. Overall, the 30-ft transit bus causes 17 to 19 percent of the damage caused by the 3-S2 reference truck, while the 40-ft transit bus causes 28 to 31 percent. These values indicate that although the potential pavement damages are comparable or greater than that of the reference truck, the cumulative effects of the number of repetitions or passes indicate that buses cause only a fraction of the damage caused by the reference truck. This is because the level of usage or the number of load repetitions from the buses is much less than the VMT from the 3-S2 reference truck.

Table 4 shows that relative pavement damage from transit buses on urban interstates is higher than on rural interstates. This is probably because the VMT for buses on urban interstates are higher than on rural interstates and vice versa for the reference truck. It should be noted the VMT values in the Highway Statistics (U.S. DOT, 2000) do not distinguish between transit and other buses. The VMT for all buses, including school buses, transit buses, and motor coaches, are lumped together. Therefore it is likely that VMTs for transit buses are overestimated, especially on rural highways. Furthermore, there is no distinction between the VMT for 30-ft and 40-ft transit buses. Therefore the results reported are general indications of the relative level of damage, assuming the annual VMTs are comparable.

Table 4. Ranges of relative ESAL–VMT by highway class

Vehicle	**Roughness (in/mile)**	**Functional Highway Class**				
		Rural Interstate	**All Rural Highways**	**Urban Interstate**	**All Urban Highways**	**All roads 10km/h - 110km/h**
30-ft Transit Bus (GVW = 31,200-lbs)	60	0.089 – 0.092	0.185 – 0.192	0.109 – 0.113	0.166 – 0.172	0.177 – 0.184
	110	0.090 – 0.092	0.186 – 0.192	0.110 – 0.113	0.167 – 0.172	0.178 – 0.184
	170	0.089 – 0.098	0.185 – 0.204	0.109 – 0.120	0.165 – 0.182	0.177 – 0.194
40-ft Transit Bus (GVW = 38,100-lbs)	60	0.143 – 0.150	0.292 – 0.312	0.175 – 0.184	0.265 – 0.279	0.284 – 0.298
	110	0.144 – 0.151	0.300 – 0.314	0.176 – 0.185	0.267 – 0.280	0.286 – 0.292
	170	0.143 – 0.155	0.298 – 0.323	0.175 – 0.190	0.266 – 0.288	0.288 – 0.308
45-ft Motor Coach (GVW = 44,400-lbs)	60	N/A	N/A	N/A	N/A	0.062 – 0.064
	110					0.060 – 0.068
	170					0.063 – 0.072

N/A – VMT data not available

The annual average VMT for motor coaches was derived from ABA (2000). The data were not broken down into highway functional classes. Consequently, only the overall ESAL-VMT values were calculated and expressed as fractions of the values for the 3-S2 reference truck. The results indicate that pavement damage from motor coaches is only 6.2 to 6.6 percent of the damage caused by 3-S2 trucks on an annual basis. It is also interesting to note that although the ESAL per vehicle for the motor coach and 30-ft transit bus are similar, the total amount of pavement damage caused by motor coaches operating on the highway network in a year is less than half of the damage caused by 30-ft buses and just about 20 percent of damage by 40-ft transit buses.

The discussions presented above are based on pavement damage relative to the reference truck in an attempt to provide a perspective on the contribution of transit buses to total pavement damage. Even though the results indicate that the contribution of transit buses to total pavement damage is insignificant, it is recognized that repeated passage of buses cause pavement deterioration in bus bays and curb lanes in urban areas. In bus bays, the static loads from stationary buses impose higher pavement damage than dynamic loads from moving buses.

7 CONCLUSIONS

The impacts of transit bus and motor coach operations on highway pavements are evaluated in terms of load-associated deterioration effects measured by the VMT weighted ESAL. The following are the concluding remarks:

Pavement damage generally increases with pavement surface roughness and vehicle speed. For very good pavements, the effect of vehicle speed on ESAL is negligible. Vehicles potentially impose higher distresses on pavements in fair condition when driven at relatively high speeds.

Pavement damage from of a 40-ft transit bus on a given pavement surface, is between 58 and 62 percent higher than the impact of a 30-ft transit bus driven at the same speed. Also, the potential pavement damage from a 30-ft transit bus, motor coach, and 3-S2 truck are comparable when operated at similar speeds and on identical pavement surfaces.

In terms of total pavement damage on interstate highways measured by VMT weighted ESAL, the 30-ft transit bus causes 9 to 12 percent of the damage caused by the 3-S2 reference truck, while the 40-ft transit bus causes 14 to 19 percent.

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