COMPUTER MODELING OF TRANSIT BUSES IN ASSESSING ROAD DAMAGING POTENTIAL

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ABSTRACT

Fully-loaded transit buses and coaches often exceed the maximum permissible axle weights allowed by the federal law on the United States Interstate Highway System. While it is widely understood that overweight trucks operating on the Interstate System contribute significantly to road wear, the extent of damage caused by overweight buses and coaches has not been fully investigated. This paper describes the results of the first phase of a study undertaken in order to determine the level of static and dynamic loads applied by buses and coaches to pavements and to assess their road damaging potential. Axle weight data were reviewed for a representative population of buses. A mathematical model of a transit bus equipped with an air spring suspension was derived . The model is employed in computer simulation of bus-road interaction to determine dynamic loads generated by a transit bus over a typical range of axle weights. Other parameters whose effects on bus wheel forces were studied included road roughness and vehicle speed. Preliminary results of the computer simulation for three levels of road roughness, three speeds, and three static axle loads are presented. In the next phase of the study, the results of the computer simulation will be combined with estimates of highway usage by buses and coaches as a percentage of average daily traffic to evaluate the extent of road wear attributable to buses and coaches.

INTRODUCTION

To protect the civil infrastructure of the Unites States Interstate System highways, the federal law limits the total weight as well as individual axle weights of the vehicle traveling on the Interstate roads and bridges. The maximum weights allowed on the Interstate System are 20,000 lbs (9091 kg) on a single axle, 34,000 lbs (15455 kg) on a tandem axle, and 80,000 lbs (36364 kg) gross vehicle weight. In addition, the vehicles must satisfy the Bridge Formula, which limits the weights on groups of axles in order to reduce the risk of damage to highway bridges. Transit buses and coaches, which often exceed the maximum permissible axle weights when fully loaded, have been temporarily exempted from the axle weight limitations. In studies of traffic-induced pavement wear, the primary focus has been on heavy trucks, while the impact of buses has received only sporadic attention [1]. A study has recently been undertaken to determine the extent of pavement wear caused by overweight buses and coaches. The results of the study will be taken into consideration to decide if the exemption from the axle weight limits for transit buses and coaches should be granted.

REVIEW OF BUS AXLE LOADS

The population of buses that are in service over the United States Interstate Highways includes a variety of vehicle types that range from modified minivans to large articulated transit coaches. The smaller paratransit vehicles and mid-size buses usually have static axle weights far below the single axle weight limits whereas large, heavy-duty buses and coaches often exceed axle weight limits when fully loaded. This study focuses on axle loads generated by heavy-duty transit vehicles that exceed 10 meters in length, including inter-city transit buses and intra-city coaches.

Inter-city transit buses are typically 12-meter long and are equipped with a single rear axle. The two-axle configuration results in high single axle loads at the rear, drive axle. Several municipalities operate articulated transit coaches, equipped with three axles, that can reach 18 meters in length. Intra-city, over-the-road, coaches are typically 14-meter long and are equipped with a tag axle. While these vehicles are usually larger and heavier than a conventional transit bus, the additional rear tag axle provides for a more even load distribution resulting in lower single axle loads. In general, bus manufacturers are challenged with trying to achieve a balance between a reduction in structural weight and improved structural durability while maintaining or even increasing passenger capacity. The weight problem is compounded by the addition of heavy components associated with advanced drivetrain technologies, alternative fuels, and passenger comfort and assist devices.

The axle weight data were collected from the Federal Transit Administration's Bus Testing and Research Center, operated by the Pennsylvania Transportation Institute. All new and modified transit bus models that are considered for purchasing with federal funds must be tested at the center. Almost 200 buses completed the test program since its inception in 1989. The population of tested vehicles includes virtually all models of transit buses that are currently in service in the United States, including alternative fuels, advanced designs, composite materials, and electric/hybrid-electric buses. An extensive amount of vehicle data have been compiled, including static axle weight measurements. The measurements are conducted for three loading conditions, representing actual operating conditions: curb weight (no passengers), seated load weight (seated passengers only), and gross vehicle weight (seated and standing passengers). Passenger loading is simulated using ballast of 68 kg for every seated and standing passenger position, including the driver.

Axle weight data were collected for thirty-eight 10-meter buses and thirty-four 12-meter buses tested during a period of 1990 to 2001. The results for front and rear axles of all vehicles in the two bus categories are presented in figures 1 and 2. The curves in figures 1 and 2 show the percentage of vehicles in the population of buses having axle loads equal to or less than the corresponding axle weight values. The six curves refer to front and rear axle weights at three load levels: curb weight (CW), seated load weight (SLW), and gross vehicle weight (GVW).

As can be seen from the plots, the front-axle weights for all buses in both 10-meter and 12-meter groups are well below the maximum single-axle weight limit of 20,000 lbs (9091 kg). However, the measured rear axle weights do exceed the limit in most of the 12-meter buses and also in a few of the 10-meter buses. Among the 10-meter buses, 3 vehicles or 8% of the population sampled exceed the single-axle weight limit in both "seated passengers only" (SLW) and in "fully loaded" (GVW) conditions. The axle overweight problem reaches alarming proportions in the 12-meter bus category, where actual rear-axle weights exceed the maximum weight limit in 83% of buses with seated passengers only and in 86% of buses under GVW condition. Table 1 summarizes the axle weight data and their compliance with the axle weight limits.

SIMULATION MODEL OF BUS DYNAMICS

In this section, a nonlinear dynamic model of a transit bus is developed to simulate the rear axle dynamic load. As shown in figure 3, the model comprises of 7 degrees of freedom: pitch ψ , roll ϕ and bounce z_m of the sprung mass, as well as roll ϕ_{u1} , ϕ_{u2} and bounce z_{u1} , z_{u2} of the front and rear unsprung masses, respectively. The equations of motion can be written as follow:

$$\begin{split} m_{u1}\ddot{z}_{u1} &= F_5 + F_6 - F_1 - F_2, \\ m_{u2}\ddot{z}_{u2} &= F_7 + F_8 - F_3 - F_4, \\ I_{url}\ddot{\phi}_{u1} &= l_{url}(F_6 + F_1 - F_5 - F_2), \\ I_{ur2}\ddot{\phi}_{u2} &= l_{ur2}(F_8 + F_3 - F_7 - F_4), \\ m\ddot{z}_m &= -(F_5 + F_6 + F_7 + F_8) + mg, \\ I_r\ddot{\phi} &= S_1(F_5 + F_7) - S_2(F_6 + F_8), \\ I_p \ddot{\psi} &= L_2(F_7 + F_8) - L_1(F_5 + F_6) \end{split}$$
(1)

where m_{ul} , m_{u2} are the masses of the front and rear axles, respectively; *m* is the sprung mass; I_{url} , I_{ur2} , and I_r are the roll moments of inertia of the front axle, the real axle, and the sprung mass, respectively; I_p is the pitch moment of inertia of the sprung mass; l_{url} and l_{ur2} are the distances from the roll centers of the front and rear axles to one of

their suspension mounting points, respectively; L_1 , L_2 , S_1 , and S_2 indicate the position of the sprung mass' center of gravity with respect to the wheels; $F_1 \sim F_4$ are the tire forces; and $F_5 \sim F_8$ are the suspension forces. The tires are simply modeled as point-contact springs. The tire forces are

$$F_{1} = k_{tf1}(z_{u1} - S_{1}\phi_{u1} - u_{f1})$$

$$F_{2} = k_{tf2}(z_{u1} + S_{2}\phi_{u1} - u_{f2})$$

$$F_{3} = k_{tr1}(z_{u2} - S_{1}\phi_{u2} - u_{r1})$$

$$F_{4} = k_{tr2}(z_{u2} + S_{2}\phi_{u2} - u_{r2})$$
(2)

where k_{ii} 's are the tire spring constants, i = fl, f2, r1, r2; Subscripts f1, f2, r1, and r2 indicate front left, front right, rear left, and rear right, respectively; and u_{fl} , u_{f2} , u_{rl} , u_{r2} are the input road profiles to the wheels.

The suspension forces consist of the restoring forces F_{ksi} 's and the damping forces F_{csi} 's, which are generated from air springs and shock absorbers, respectively,

$$F_{5} = F_{kgf1} + F_{cgf1}$$

$$F_{6} = F_{kgf2} + F_{cgf2} \qquad (3)$$

$$F_{7} = F_{ksr1} + F_{csr1}$$

$$F_{8} = F_{ksr2} + F_{csr2}$$
The damping forces are approximated by piecewise linear functions as
$$F_{csi} = b_{i}\dot{z}_{suspi} + a_{csi}, \quad i = f1, f2, r1, r2 \qquad (4)$$

where, the suspension deflections are calculated from the following equations

$$z_{suspf1} = z_m - S_1 \phi - L_1 \psi - (z_{u1} - S_1 \phi_{u1})$$

$$z_{suspf2} = z_m + S_2 \phi - L_1 \psi - (z_{u1} + S_2 \phi_{u1})$$

$$z_{suspr1} = z_m - S_1 \phi + L_2 \psi - (z_{u2} - S_1 \phi_{u2})$$

$$z_{suspr2} = z_m + S_2 \phi + L_2 \psi - (z_{u2} + S_2 \phi_{u2})$$
(5)

The coefficients b_i and a_i in Equation (4) depend on the suspension deflections' time derivatives [2]. For front suspension, $i = fI_i f_i^2$,

If $z_{suspi} > 0.2 \text{ m/s}$, then $b_i = 3.4$ (KN-s/m), $a_i = 1.4$ (KN) If $0m/s < z_{suspi} < 0.2m/s$, then $b_i = 7$ (KN-s/m), $a_i = 0$ (KN) If $-0.3m/s < z_{suspi} < 0m/s$, then $b_i = 29.4$ (KN-s/m), $a_i = 0$ (KN) If $z_{suspi} < -0.3 \text{ m/s}$, then $b_i = 11.8$ (KN-s/m), $a_i = -8.82$ (KN) For rear suspension, i = r1, r2, If $z_{suspi} > 0.2 \text{ m/s}$, then $b_i = 3.9$ (KN-s/m), $a_i = 3.22$ (KN) If $0m/s < z_{suspi} < 0.2m/s$, then $b_i = 16.1$ (KN-s/m), $a_i = 0$ (KN) If $-0.3m/s < z_{suspi} < 0m/s$, then $b_i = 40$ (KN-s/m), $a_i = 0$ (KN) If $z_{suspi} < -0.3 \text{ m/s}$, then $b_i = 22.4$ (KN-s/m), $a_i = -12$ (KN)

Transit buses are commonly equipped with pneumatic suspensions because of their practical advantages, such as road friendliness, as well as a constant suspension frequency and ride height regardless of the vehicle load. A number of air spring models have been developed. Some of them are focused on thermodynamic characteristics of the air suspension, while others concentrate on the force-deflection relationship. These models are either linear or nonlinear, but always with constant model parameters. In other words, the influence of preload (or static load) on the stiffness and/or on the model parameters has not been fully addressed in the existing models.

From the measured data shown in figure 4, the air springs show nonlinear characteristics with respect to the deflection, often with an increased stiffness at larger deflections. Furthermore, the air springs become stiffer when static load increases. For instance, the approximate stiffness of one front axle air spring may vary from 21KN/m to 75KN/m when the loading condition varies from curb weight to fully loaded with passengers. Considering that the loading condition of the transit buses may vary significantly from trip to trip, it is necessary to take the preload factor into account for a more realistic model of the transit bus dynamics.

In this paper, to represent nonlinear force-deflection relationship as well as to account for the preload dependence, the air spring force is modeled as a fourth-order polynomial function. Since the bus modeled in this paper has four air bags per axle, the suspension spring forces are formulated as follow:

$$F_{ksi} = 2(k_{i0} + k_{i1}z_{suspi} + k_{i2}z_{suspi}^2 + k_{i3}z_{suspi}^3 + k_{i4}z_{suspi}^4) \qquad i = f1, f2, r1, r2$$
(6)

where the coefficients k_i depend on the loading condition

 $k_{ij} = a_{ij} + b_{ij} \cdot P_j$ i = fl, f2, rl, r2 $j = 0, l, \dots, 4$ (7)

where P_j is the static load on the spring, and the coefficients a_{ij} and b_{ij} are obtained from fitting the experimental data.

PRELIMINARY RESULTS

< >=n;

To assess the extent of road damage contributable to transit buses and coaches traveling on the Interstate System highways, the computer model of bus dynamics will be subjected to actual road profiles measured on interstate highways and covering a representative range of roughness. In the preliminary stages of the study reported in this paper, the road profile was generated artificially following the approach described in [3].

The road profile is modeled as a homogeneous Gaussian random process with zero mean and power spectral density, S(k), defined as

$$S(k) = \begin{cases} S(k_0) \left(\frac{k}{k_0}\right)^{-n_2} & k \le k_0 \\ S(k_0) \left(\frac{k}{k_0}\right)^{-n_2} & k > k_0 \end{cases}$$
(8)

where k is the wave number in cycles/m, $k_0 = 1/2\pi$ (cycles/m); n_1 and n_2 are the spectral slope coefficients. According to ISO classification of road types, $S(k_0)$ ranges from 2 to 2028, $n_1 = 2$, $n_2 = 1.5$. The single road profile is generated by

$$z(j) = \sum_{m=0}^{N-1} \sqrt{\frac{2\pi}{N\Delta} S(\frac{2\pi m}{N\Delta})} e^{i(\vartheta_m + \frac{2\pi m}{N})} \qquad j = 0, 1, 2, \dots, N-1$$
(9)

where Δ is the distance interval between successive ordinates of the profile and ϑ_m is a set of independent random phase angles uniformly distributed between 0 and 2π . The generated road profiles are shown for three different values of International Roughness Index (IRI) are shown in figure 5.

The bus model derived in the previous section was simulated using the three road profiles, three levels of axle weights, and three speeds. The output variable in the simulation was the Dynamic Load Coefficient (DLC) defined as the ratio of the standard deviation of dynamic wheel load over the mean wheel load. Figures 6, 7, and 8 show the values of DLC versus static axle load and speed for three levels of road roughness. As expected, the DLC increases with increasing speed and road roughness.

FURTHER RESEARCH

The computer model of a transit bus equipped with air spring suspension presented in this paper will provide a tool for evaluating dynamic wheel loads generated by transit buses traveling on interstate highways.

To evaluate the road damaging potential of transit buses, the pavement cost responsibility of buses will be determined and compared to the pavement cost responsibility of a 5-axle tractor-trailer combination. The pavement damage will be estimated using the equivalent standard axle load (ESAL) weighted by an average annual vehiclemiles traveled (VMT)[4]. Furthermore, the impact of future changes in bus design standards, such as new materials, alternative fuels, and new propulsion systems, including hybrid-electric and fuel cell buses, on highway wear will be evaluated.

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TABLES & FIGURES

Table 1 - Percentages of buses exceeding maximum allowable axle load.

		10-Meter Buses	12-Meter Buses
Number of Bus Models	38	32	
Number of Sample Buses	38	34	
	CW	0%	0%
Front Axle Overweight Percentage	SLW	0%	0%
	GVW	0%	0%
	CW	0%	23%
Rear Axle Overweight Percentage	SLW	8%	83%
	GVW	8%	86%

*CW - curb weight

*SLW - seated load weight

*GVW - gross vehicle weight



Figure 1. Statistical distribution of single-axle weights for 10-meter buses.



Figure 2. Statistical distribution of single-axle weight for 12-week buses.



Figure 3 - The vehicle dynamic model.



(b)

Figure 4 - Modeling of nonlinear air spring force

- (a) Front Axle Air Spring;
- (b) (b) Rear Axle Air Spring



Figure 5 - Generated road profiles with IRI equal to 1.5 mm/m (a), 2.5 mm/m (b), and 5.1 mm/m (c).







Figure 7 - DLC versus axle load and vehicle speed for IRI = 2.5 mm/m.



Figure 8 - DLC versus axle load and vehicle speed for IRI = 5.1 mm/m.

