EFFECTS OF WEIGHT ON PERFORMANCE OF TRANSIT VEHICLES

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ABSTRACT

The incorporation of heavy components into new drive systems, alternative fuel technologies, and passenger assistance devices has led to significant increases in the gross weight of transit vehicles in recent years. It has been reported that almost 90% of large (12 m in length) transit buses exceed the maximum single-axle loads allowed in the United States. The increased weight has a strong influence on important performance characteristics such as level of dynamic tire forces, stopping distance, roll stability, and emissions. The focus of this paper is on those performance characteristics that affect the safety of transit vehicles. The results presented come from experimental testing of transit buses conducted at the Federal Transit Administration's Bus Testing Center operated by the Pennsylvania Transportation Institute and from computer simulation.

INTRODUCTION

The Pennsylvania Transportation Institute of the Pennsylvania State University operates the Bus Testing Program for the U.S. Federal Transit Administration. All new and modified transit bus models that are considered for purchasing with federal funds must complete the testing program. The buses are tested for maintainability, structural integrity and durability, reliability, safety, performance, noise, and fuel economy (Klinikowski et al., 1997). A braking test will be added to the program in the near future. Over 240 vehicles, ranging from modified minivans to full-size, heavy-duty transit buses, have been tested since the program's inception in 1989. An extensive set of data has been generated in the course of testing. The results of the most recent tests conducted on over 50 different bus models are accessible on the web at http://edog.mne.psu.edu/pti/. The bus test reports were the primary source of data for the findings presented in this paper.

The recent technological advances in bus design reviewed in the companion paper (Klinikowski et al., 2004) have often been accomplished at the cost of increased vehicle weight. One commonly recognized concern associated with increased weight is its impact on damage caused to the civil infrastructure – roads and bridges – due to excessive wheel loads. The effect of vehicle weight on road and bridge damage has been extensively documented for heavy trucks and well documented for transit buses and coaches (Kulakowski et al., 2003). The effects of weight on other performance characteristics of transit buses have not been adequately addressed. The main objective of this paper is to assess the effect of weight on selected characteristics of transit buses, including the level of wheel loads, stopping distance, roll stability, and emissions.

EFFECTS OF WEIGHT ON WHEEL LOADS

In urban areas, pavement wear resulting from wheel loads applied by heavy-duty transit buses has been identified as a high-cost maintenance problem. Vehicle weight, along with vehicle speed and road roughness, is the primary factor affecting the level of static and dynamic wheel loads and the extent of pavement wear induced by the vehicle/road interaction. To protect the civil infrastructure, maximum allowable limits are imposed on vehicle weight and/or vehicle weight per axle. In the United States, the maximum gross vehicle weight allowed on interstate highways is 356.7 kN. Axle loads are limited to 89.2 kN on a single axle and 151.7 kN on a tandem axle. However, transit buses are exempted from those limits. In 2002, a study sponsored by the Federal Transit Administration was undertaken to investigate the level of static and dynamic loads applied by overweight transit buses and coaches operated on the United States interstate highway system and to assess their road damaging potential (Kulakowski et al., 2002). A survey of the data for 72 heavy-duty (10- and 12-m long) bus models revealed that all buses had their gross weight below the limits, but because they are typically equipped with a single rear axle, most (almost 90%) of the 12-m buses exceeded the maximum allowable weight per axle. The results of the survey are summarized in Table 1.

Table 1. Percentages of buses exceeding maximum allowable axle weight.

	Loading Condition	10M BUSES	12M BUSES
Testing Date		1990 ~ 2001	1990 ~ 2001
Number of Bus Models		38	32
Number of Samples		38	35
Front Axle Overload Percentage (%)	CW	0	0
	SLW	0	0
	GVW	0	0
Rear Axle Overload Percentage (%)	CW	0	23
	SLW	0	83
	GVW	8	86

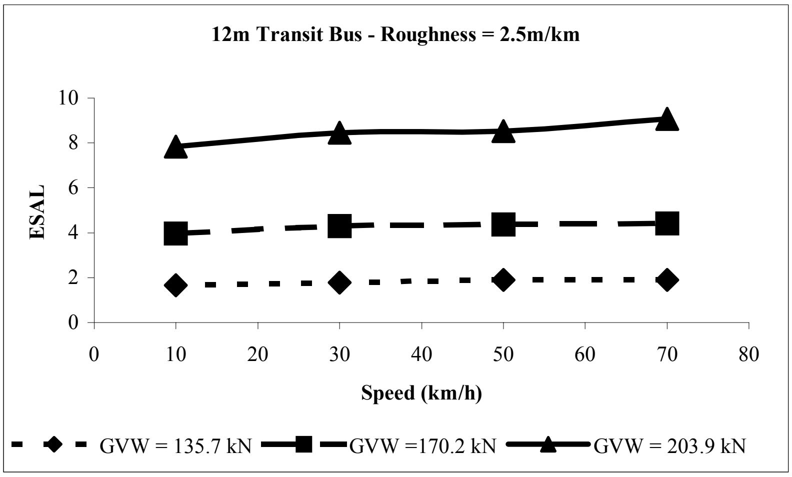


Figure 1. Effect of speed on ESAL.

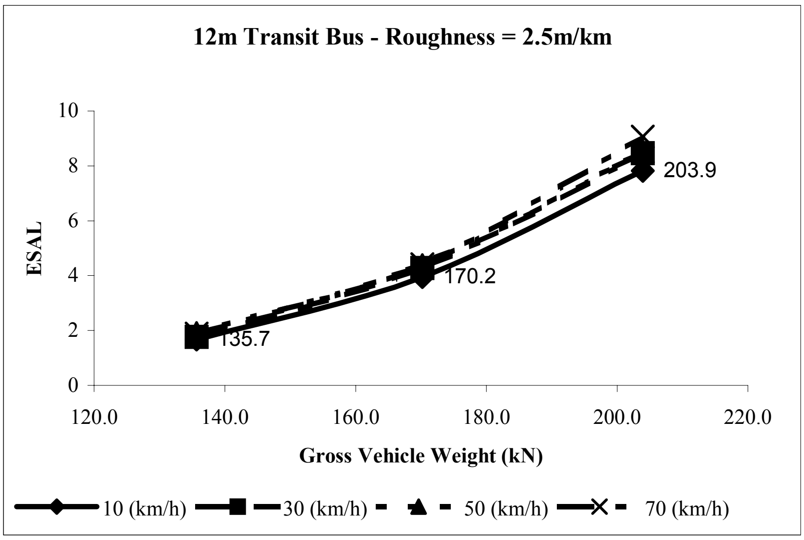


Figure 2. Effect of gross vehicle weight on ESAL.

To evaluate the impact on pavement wear, a method used in cost allocation studies and based on equivalent single axle loads (ESALs) modified to account for dynamic component of wheel loads was employed (Fekpe, 1999). The wheel load results were obtained from computer simulation of a 12-m bus traveling on a relatively rough road with IRI = 2.5 m/km under three different payloads resulting in gross vehicle weights of 135.7, 170.2, and 203.9 kN. The ESALs for the three payloads and speeds from 10 to 70 km/hr are shown in Figures 1 and 2. It can be seen that the ESALs increase in a nonlinear fashion when the gross vehicle weight increases. For instance, the ESAL value for the light bus at 50 km/hr is 1.9, but it is more than doubled for the medium-weight bus (4.4) and more than quadrupled for the heavy bus (8.5). It is quite obvious that reducing bus weight by using lightweight composite materials or other means to offset the increased weight of CNG tanks, electric batteries, and fuel cells in new bus models will contribute significantly to longer pavement life on transit bus routes.

EFFECTS OF WEIGHT ON STOPPING DISTANCE

The sheer weight of a heavy vehicle and the different operating conditions that it encounters pose a significant challenge to the brake designer. The brake system of a heavy vehicle is not only larger than that of a passenger car, but also much more complex. Stopping distance tests are a standard means of evaluating brake performance. As a part of this study, stopping distance tests were conducted on two buses - a low-floor, full-size transit bus with a GVWR (Gross Vehicle Weight Rating) of 186.4 kN and a smaller, 14-seat bus with a GVWR of 42.8 kN. Tests were conducted under two different loading conditions – fully laden and partly laden with only seated passengers - on a dry test track. The skid number, measured as per ASTM Standard E 274 for brake test patch at 64 km/h (SN_{40}) with a ribbed tire, was found to be 75. The loading conditions for the two buses are given in Table 2.

Table 2. Brake test loading conditions for the two buses.

	Loading Condition	Front Axle Weight, kN	Rear Axle Weight, kN	Total Vehicle Weight, kN
Low Floor Transit bus	Fully Laden	63.2	116.7	179.9
	Partly Laden	47.2	99.8	147.0
14-Seat bus	Fully Laden	16.2	26.2	42.4
	Partly Laden	14.6	23.5	38.1

The test methodology consisted of driving the bus to a speed slightly higher (approximately +8 km/h) than the desired test speed, stabilizing the vehicle at the desired test speed and then applying the brakes in a stable manner. The buses were equipped with an anti-lock braking system (ABS) and braking effort was modulated so that premature lockup was practically reduced/eliminated. For each loading condition, tests were conducted at four different speeds: 32 km/h, 48 km/h, 64 km/h, and 80 km/h. The test results obtained are shown in Figures 3 and 4.

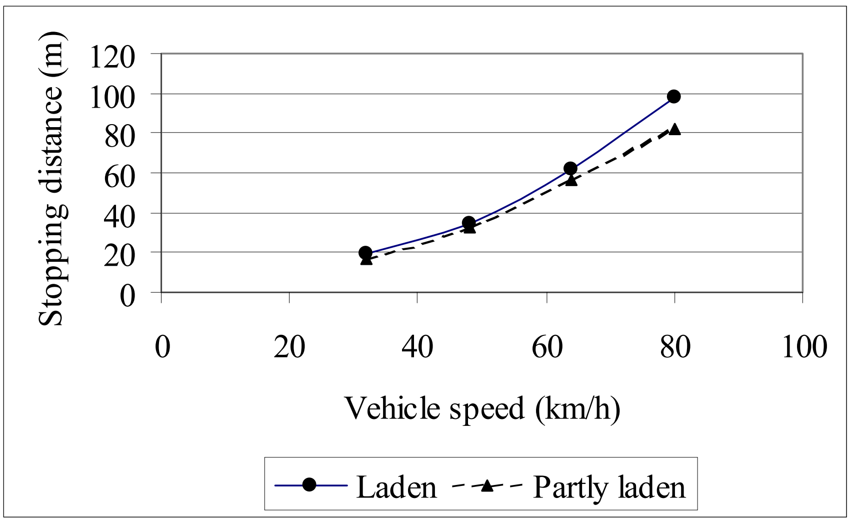


Figure 3. Effect of loading conditions on stopping distance – low-floor bus.

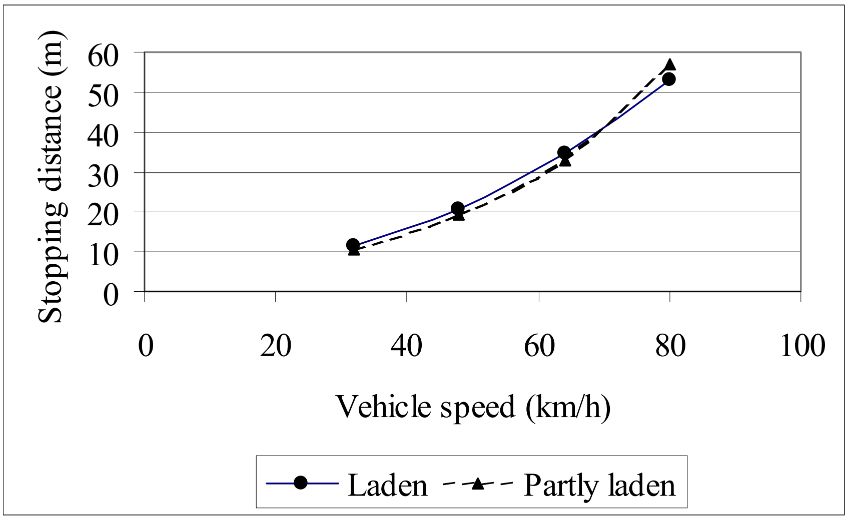


Figure 4. Effect of loading conditions on stopping distance – 14-seat bus.

The test results indicate that stopping distances in general increase with increase in vehicle weight at normal operating speeds for buses. This seems to be in line with the trend observed for two-axle heavy vehicles (FMCSA, 2000). However, at high speeds the stability of an empty or partly laden vehicle becomes an issue. This possibly explains the longer stopping distance observed for the partly laden 14-seat bus at 80 km/hr. During the said test the bus was found to be yawing.

EFFECTS OF WEIGHT ON ROLL STABILITY

Rollover accidents constitute a very serious transportation safety issue for all types of vehicles. In recent years, substantial attention has been given to the causes of and potential solutions for the rollover accidents involving sport utility vehicles (SUVs) and heavy-duty trucks. The roll stability of buses has been given only rudimentary treatment. As shown in Figure 5, over 8% of bus rollover accidents involve a fatality, which is considerably higher than for all other types of vehicles, including SUVs (NHTSA, 2001).

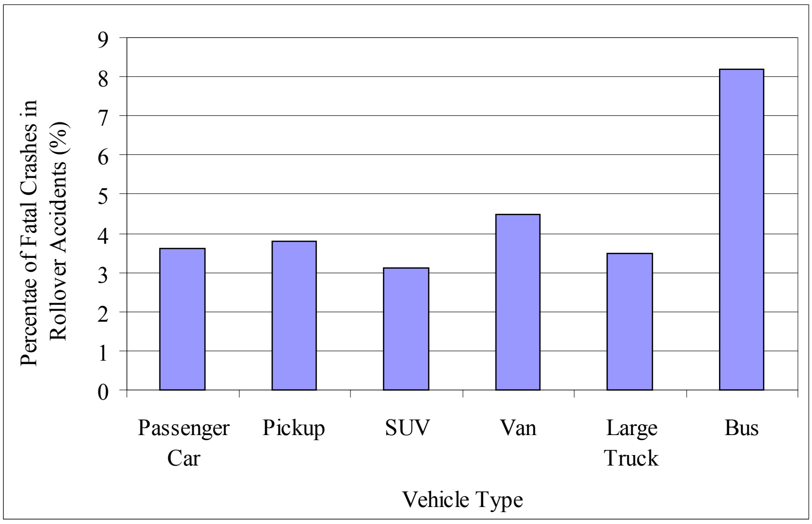


Figure 5. Percentage of rollover accidents involving fatalities by vehicle type.

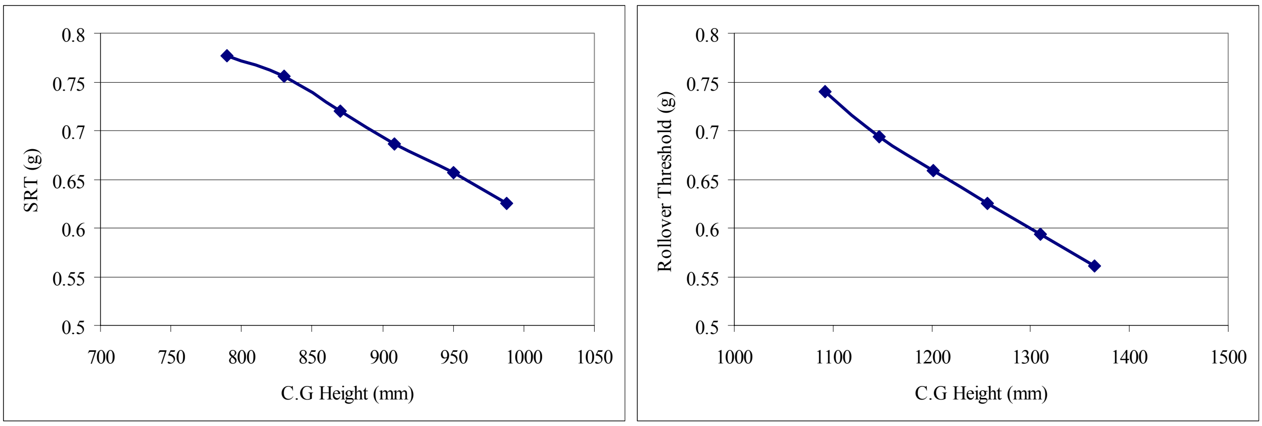
Rollover accidents may occur as a result of one of many vehicle, driver, or road-related factors or from combinations of those factors. Among the vehicle characteristics that have been investigated, static roll stability is one of the most strongly related to the probability of rollover accidents (Winkler et al., 1993). A commonly used criterion representing the static roll stability is static rollover threshold (SRT). In this study, the SRT, defined as the maximum level of steady lateral acceleration a vehicle can stand without overturning in a steady turn, was used as a measure of roll stability. To evaluate the effect of weight on roll stability, computer simulation of a 12-m heavy-duty transit bus and a 6-m minibus was conducted for a range of center of gravity (c.g.) heights, gross vehicle weights, and weight distributions between axles of the two buses.

The computer simulation was performed using MSC ADAMS 12.0. In the computer model, the vehicle body is considered to be rigid and symmetric with respect to its longitudinal axis. The composite roll stiffness of the suspension system was modeled as a linear torsional spring with different spring constant values assigned to the front and rear suspensions. The tires were modeled as linear springs having a point of contact with the ground. The friction between the tires and pavement was assumed to be sufficient to prevent the vehicle from lateral skidding. The values of SRT were found by simulating a vehicle running with a constant steer angle and an increasing speed, an operation that causes the vehicle to follow a spiral of increasing radius. The lateral acceleration at the time when the contact force between the ground and the inner tire on the rear axle becomes zero is considered to be the SRT (Mueller and Baas, 2001). To evaluate the effect of three variables, c.g. height, vehicle weight, and weight distribution, three series of computer simulations were performed with only one variable varying and the other two kept constant in each series. While this does not represent a realistic situation, it offered the simplest way for demonstrating the effect of each test variable on roll stability. The nominal values of the three test variables for the two bus types are shown in Table 3.

In the first series, vehicle c.g. height was varied while gross vehicle weight and weight distribution between the front and rear axles were kept constant and equal to their nominal values. The results of the simulation are presented in Figures 6a and 6b for the 6-m bus and the 12-m bus, respectively. As expected, the SRT for both buses decreases in an approximately linear fashion when c.g. height increases.

Table 3. Nominal values of vehicle weight and weight distribution.

	C.G. Height [mm]	GVW [kN]	Front/Rear [%]
6-meter Bus	790	45.0	47/53
12-meter Bus	1095	170.2	27/73

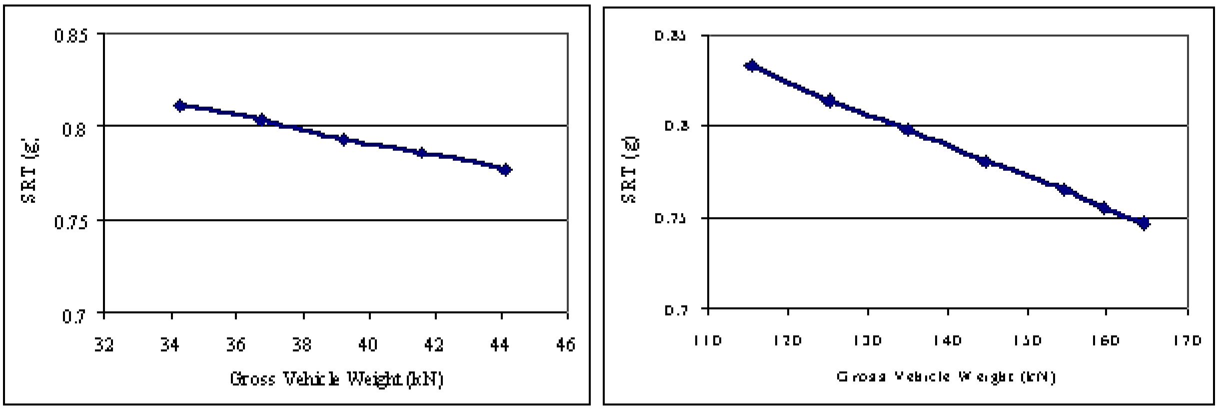


(a) (b)

Figure 6. Effect of c.g. height on SRT for a 6-m (a) and a 12-m (b) bus.

The effects of gross vehicle weight on roll stability of the two buses are shown in figures 7a and 7b. Since the increased vehicle weight causes larger compliance in the suspension system and tires under the same lateral acceleration, the SRT is consequently lowered when the weight increases. It can be observed that the SRT decreases proportionally with the increase in vehicle weight for both buses. A 10% increase in gross vehicle weight results in a 2.4% reduction in SRT for the 12-m bus and a 1.5% reduction for the 6-m bus.

Finally, the effects of weight distribution between the front and rear axles of the bus were examined with the c.g. height and gross vehicle weight constant. The results of computer simulation for both buses are shown in Figure 8. As can be seen, the arrangement of load distribution between front and rear axles influences SRT values for fixed values of gross vehicle weight and C.G. height. For the 12-m transit bus, a greater reduction in rollover threshold results from the placement of a greater fraction of the load on the steering axle. A 10% increase in the load distribution on the front axle yields an average of 6% reduction in rollover threshold. This observation reflects the fact that the steering axle of a heavy-duty vehicle usually has substantially lower roll stiffness than its rear suspension. For the 6-m minibus, although the roll stiffness values of the front and the rear suspensions are fairly close, an average of 13% reduction in SRT for every 10% increase in the load distribution on the front axle was observed as a result of the extremely low height of the front suspension roll center.



(a) (b)

Figure 7. Effect of gross vehicle weight on roll stability for a 6-m (a) and a 12-m (b) bus.

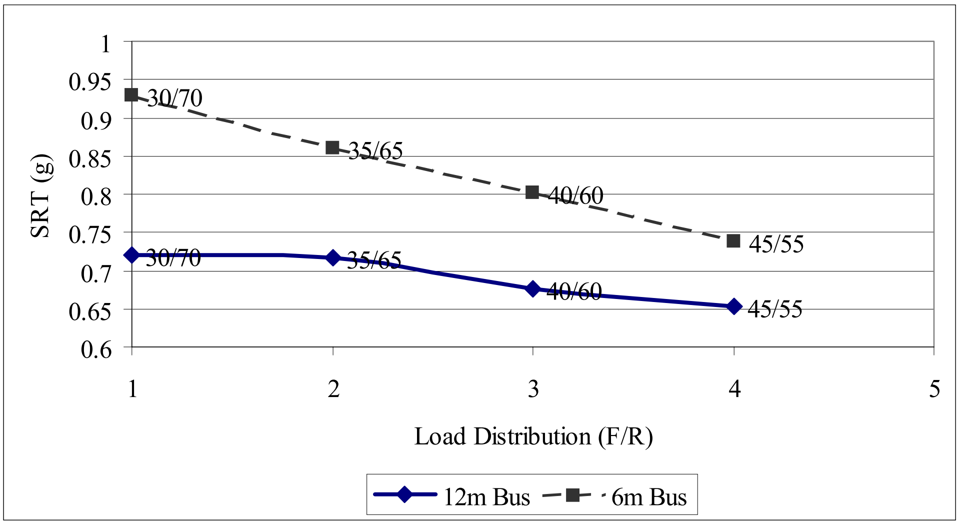


Figure 8. Effect of axle-load distribution on roll stability for a 6-meter and a 12-meter bus.

EFFECTS OF WEIGHT ON EMISSION

In general, an increase in vehicle weight results in increased exhaust emissions, both directly and indirectly. Because the vehicle requires more power when overloaded, there is a tendency to over-fuel the engine. Over-fueling, in turn, causes significantly higher black smoke emissions (The World Bank, 2002). An indirect effect of overloading is an increase in wear of engine, tires, brakes, and other vehicle components. An ill-serviced vehicle emits considerably more pollutants under such conditions.

Computer simulations have been conducted to reveal the effect of vehicle weight on exhaust emissions (Koskinen and Sauna-Ho, 1998). It was found that an increase of weight from 394.2 to 588.6 kN, for a vehicle operating in an urban environment at 50 km/h, increases the fuel consumption, oxides of nitrogen (NO_x), and hydrocarbons (HC) emissions by 34%, 33%, and 10%, respectively. Interestingly, however, when considered per metric ton-km of travel, the values of fuel consumption, NO_x, and HC emissions decreased by 24%, 25%, and 38%.

Based on these results, it appears that the increase in weight of transit buses clearly contributes to increased emissions. However, it appears also that it is beneficial to operate fewer buses that will carry more passengers than to operate more buses with a reduced passenger load.

CONCLUSIONS

Some of the changes implemented in new bus technologies in response to new regulations and/or as a result of availability of new propulsion systems often result in increased weight of the new vehicles. This paper examined the effects of the increases in vehicle weight on importance performance characteristics, including the level of static and dynamic wheel loads, stopping distance, roll stability, and exhaust emissions. It was shown, that the magnitude of wheel loads applied by heavy buses to pavements increases in a nonlinear manner with increased axle weights. The efforts aimed at reducing the weight of buses by using lightweight materials would contribute significantly to longer life of pavements on transit bus routes. The results of field tests conducted with two models of buses, demonstrated a significant increase in the stopping distance of a full-size transit bus traveling at 80 km/hr when the bus weight increases. The effects of gross vehicle weight, height of the center of gravity, and load distribution between the axles were investigated using computer simulation. While buses are known to have considerably better roll stability than other types of vehicles, their roll performance is degraded by increased vehicle weight, which may prove critical in situations leading to a tripped rollover. Based on limited data found in literature, the increased weight also contributes to increased fuel consumption and, consequently, to an increase in emissions of oxides of nitrogen and hydrocarbons.

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