Impact on Street Pavements of Buses Fueled by Compressed Natural Gas

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The federal Clean Air Act Amendments of 1990 and the Energy Policy Act of 1992, along with other state regulations, have stimulated or mandated the use of alternative fuels to power transit system bus fleets. Among such fuels, compressed natural gas (CNG) is attractive, even though it must be stored in robust, pressurized cylinders capable of withstanding pressures up to 34 450 kPa (5,000 psi). Such systems are typically heavier than conventional diesel storage tanks. As a result, gross vehicle weight is raised, sometimes significantly, which then increases the consumption of the pavement over which CNG buses operate. Capital Metro, the Austin, Texas, transit authority, is evaluating a number of CNG-fueled buses. As part of the U.S. Department of Transportation's University Transportation Centers Program, the scale of incremental pavement consumption associated with the operation of these buses was studied. The study suggests that replacing current vehicles with CNG-powered models using aluminum storage tanks would raise average network equivalent single-axle impacts by about 6 percent, which means an increase in total overlay rehabilitation costs across the network of more than 4 percent a year. Finally, it recommends that a full cost study be undertaken to evaluate the adoption of alternative bus fuels, including its pavement and environmental impacts.

The study evaluated the impact of both conventional diesel and compressed natural gas (CNG) transit buses on route pavement networks in Austin, Texas. Because new conventional diesel buses had already increased pavement consumption on city routes, there was a concern that even heavier CNG buses would worsen the situation. The study, sponsored by the U.S. Department of Transportation's University Transportation Centers Program (UTCP), focused on measuring this impact for setting design, performance standard, and cost recovery mechanisms for bus routes (*1*). [It should be noted that throughout this paper, the term "*consumption*" is used instead of "*deterioration.*" Since the study addressed axle load impacts (excluding broader deterioration issues such as climate) in the context of design standards, budget, and cost recovery, the term "*consumption*" was considered more accurate.]

It is well known that U.S. transportation is highly dependent on oil derivatives, more than half of which are imported (*2*). Despite improvements in vehicle fuel efficiency since the mid-1970s, aggregate petroleum consumption has continued to grow, driven principally by vehicle ownership and total miles of travel. Strategic concerns over such dependency and concern about air quality issues have combined to sustain momentum for policies that encourage the adoption of alternative fuels.

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New policies and enacting legislation include federal and state regulations, such as the Alternative Motor Fuel Act of 1988, the Clean Air Act Amendments of 1990, the Intermodal Surface Transportation Efficiency Act of 1991, and the Energy Policy Act of 1992. Although each law addresses particular issues related to transportation, all encourage the development and use of alternative fuels. In 1989 Texas became the first state to mandate the development and use of alternative fuels in certain state- and municipally owned fleets. Under this mandate, 90 percent of these fleet vehicles must be capable of operating on alternative fuels by 1998 (*3*).

Five alternative fuels have been recognized by policy makers, namely, natural gas, methanol, ethanol, propane gas, and electricity. Among these fuels, natural gas is plentiful and, accordingly, low in price. For transportation purposes, it can be stored in either liquefied or compressed forms. Liquefaction occurs when temperatures are reached below the boiling point of −161°C (−270°F), thus requiring a highly insulated and expensive storage process. Although some city transit systems (such as Houston's METRO) are experimenting with liquefied gas, natural gas in a compressed state is likely to remain the preferred alternative transit bus fuel in this decade.

However, standards require that CNG be stored in cylinders that withstand pressures of at least 34 450 kPa (5,000 psi). Cylinders can be made from steel, steel composite, or aluminum composite; because aluminum composite cylinders are about 50 percent lighter than steel cylinders, they are attractive to mechanical engineers concerned with limiting unladen vehicular weight (*4*). Usually, cylinder capacity is expressed in liters of water, with 1 cylinder liter containing 0.16 kg (0.36 lb) of natural gas at a standard working pressure of 20 670 kPa (3,000 psi) and temperature of 21°C (70°F). The ratio of the weight (diesel fuel plus tanks) to the volume of gallons of conventional diesel fuel tanks is 4.75 kg/3.785 L (10.46 lb/gal) (*5*). Using a compound factor of approximately 1.3 to include the additional weight to hold cylinders and the reduction of fuel economy due to the extra weight (*6*), the CNG bus would carry an additional 7.7 kg (17 lb) for each equivalent 3.785 L (1 gal) of conventional fuel. If a diesel bus with a typical curb weight of 12 712 kg (28,000 lb) and a 454-L (120-gal) diesel fuel capacity used CNG to achieve an equivalent mileage range, the bus would have to carry an additional 921.6 kg (2,030 lb), representing a 7.3 percent increase in unladen weight.

The CNG fuel cylinders are typically mounted under the bus floor, such as with the Transportation Manufacturing Corporation (TMC) CNG bus, the Flexible CNG bus, and the Blue Bird CNG bus. In 1993 TMC delivered 30 CNG-fueled buses, 12.2 m (40 ft) long with 43 seats, to the Capital Metro Transit System of Austin. Currently, Capital Metro operates these TMC CNG buses on several Austin routes, and these are the vehicle types used to model pavement impacts in this paper.

PASSENGER LOADING AND AXLE LOAD OF BUSES

Relationships between axle loading and pavement deterioration were developed originally at the AASHO Road Test (1958–1961), where the concept of equivalent single-axle loads (ESALs) was developed. It permits various axle loads to be expressed as units equivalent to a standard 18,000-lb axle load, which is used in pavement design work. The relationship between load and pavement damage was developed empirically and based on observations taken at the AASHO Road Test. The relative effect, to a standard 8172-kg (18,000-lb) single axle with dual tires, was related to the ratio of any specified axle load to 8172 kg (18,000 lb) raised to the fourth power (*7,8*). ESAL calculations therefore allow different bus loads—both from unladen weight and passengers—to be related to pavement consumption.

In the study of bus pavement impacts, passenger occupancy is an important factor in determining bus-ESALs. Bus payloads differ from those of trucks because loading frequencies change with boarding and alighting at a rate greater than that of typical freight hauls. The study method included a survey of occupancy rates along each route to determine passenger occupancy patterns (and loads) for calculating pavement consumption impacts.

Although it was found that passenger demand reached 1.5 times the seating capacity (about 75) at peak times, average passenger occupancy is generally between one-third to one-half seating capacity. From the survey results, route sections and average loads were categorized as follows:

1. Highest-occupancy sections (25 passengers),
2. Dense-occupancy sections (20 passengers),
3. Medium-occupancy sections (15 passengers),
4. Low-occupancy sections (10 passengers), and
5. Lowest-occupancy sections (5 passengers).

Additionally, using passenger seating patterns observed in this survey, the center of gravity of passenger loading was determined to lie at the geometric center of the seating area. From this determination the passenger loading between axles was estimated to be 0.4 on the front axle and 0.6 on the rear axle (*1*). The marginal effect of this is to further increase weight distribution on the rear axle, therefore raising ESAL values.

The ESALs of the major bus models on flexible pavements are given in Table 1. Table 2 presents the impact of passenger occupancy on the front and rear axles of the CNG and GILLIG 1100 buses in Austin. Passenger loads have a pronounced effect on ESAL impacts. An increase of occupancy from 0 to 150 percent (peak load) of seating capacity raises the total ESALs from 100 to 358 percent. At this point, the ESAL of the rear axle is 4.31 and accounts for 93 percent of total bus ESALs. The relationship between passenger occupancy and ESALs using a GILLIG 1100 bus is shown in Figure 1.

Standard ESAL analysis indicates that one loaded GILLIG 1100 bus is equivalent to 35,400 small cars [gross vehicle weight (GVW) 908 kg (2,000 lb), single-axle load equal to 454 kg (1,000 lb)], or 4,800 medium cars [GVW 1816 kg (4,000 lb), single-axle load equal to 908 kg (2,000 lb)], or 1,710 pickups [GVW 2497 kg

TABLE 1 ESAL Factor for Different Buses

	TMC CNG diesel bus		GILLIG 1100 diesel bus		GILLIG 1700 diesel bus		GILLIG 1600 diesel bus	
Seat Capacity	43		47		39		29	
Curb Weight (kg/lb.)	13,311 / 29,320		12,830 / 28,260		11,985 / 26,400		11,377 / 25,060	
	Pt=2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.5
Number of passengers	SN=2.5	3.0	2.5	3.0	2.5	3.0	2.5	3.0
0	1.349	1.347	1.292	1.287	1.040	1.057	0.970	0.987
5	1.494	1.476	1.433	1.411	1.158	1.163	1.081	1.087
10	1.653	1.615	1.586	1.544	1.287	1.277	1.203	1.195
15	1.824	1.764	1.751	1.688	1.427	1.401	1.335	1.311
20	2.009	1.923	1.930	1.842	1.579	1.533	1.479	1.436
25	2.210	2.095	2.124	2.008	1.744	1.676	1.635	1.571
30	2.425	2.278	2.333	2.185	1.922	1.829	1.804	1.717
35	2.658	2.474	2.558	2.375	2.115	1.994	1.987	1.873
40	2.908	2.684	2.800	2.578	2.323	2.170	2.184	2.040
45	3.176	2.908	3.060	2.795	2.547	2.359	2.397	2.219
50	3.464	3.147	3.339	3.027	2.788	2.561	—	—
55	3.773	3.402	3.639	3.274	3.047	2.777	—	—
60	4.103	3.673	3.959	3.538	3.325	3.008	—	—
65	4.456	3.962	4.302	3.819	—	—	—	—
70	—	—	4.668	4.117	—	—	—	—

Notes:
Pt = Pavement Terminal Serviceability (Present Serviceability Index-PSI-Units)
SN = Structural number of pavement
"—" = not applicable; seat capacity exceeds design capacity

TABLE 2 Passenger and Axle Load Distributions for CNG and GILLIG 1100 Diesel Bus

Types of Buses:		TMC (CNG)		GILLIG 1100	
Curb Weight (kg):		13,311		12,830	
Seating Capacity:		43		47	
Type of Axle		Front	Rear	Front	Rear
Passenger Load Distribution:		0.4	0.6	0.4	0.6
		Axle Load (kN)		Axle Load (kN)	
Number of Passengers	Passenger Loads (kN)	Front	Rear	Front	Rear
0	0.00	46.17	84.24	41.81	83.89
5	3.33	47.50	86.25	43.14	85.89
10	6.67	48.84	88.25	44.48	87.89
15	10.08	50.17	90.25	45.81	89.89
20	13.34	51.51	92.25	47.14	91.89
25	16.68	52.84	94.25	48.48	93.90
30	20.01	54.18	96.25	49.81	95.90
35	23.35	55.51	98.26	51.15	97.90
40	26.68	56.84	100.26	52.48	99.90
45	30.02	58.18	102.26	53.82	101.90
50	33.36	59.51	104.26	55.15	103.90
55	36.69	60.85	106.26	56.48	105.91
60	40.03	62.18	108.26	57.82	107.91
65	43.36	63.52	110.27	59.15	109.91
70	46.70	—	—	60.49	111.91

1 kg=0.453 lb
1 kN=4.448 kip
"—" = not applicable; seat capacity exceeds design capacity

(5,500 lb), single-axle load equal to 1248 kg (2,750 lb)]. Using this method, one loaded TMC CNG bus corresponds to 36,800 small cars, or 5,000 medium cars, or 1,750 pickups. Although passenger cars and pickups account for up to 90 and 9 percent of average daily traffic (ADT) on Texas city streets, respectively, the ESAL analysis showed that they have such a small influence on pavement design that consumption was linked only to bus and truck operations.

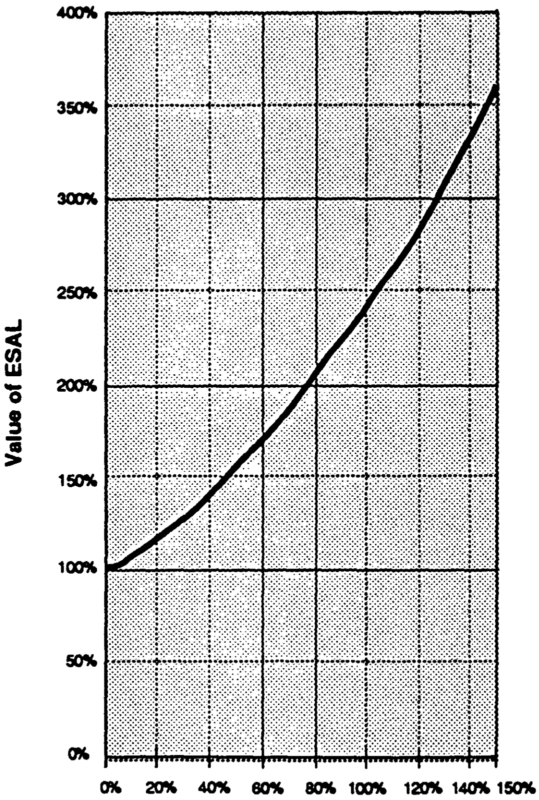

FIGURE 1 Occupancy rates versus ESAL impacts.

CNG BUS OPERATIONS

ESAL per-lane-mile calculations were chosen to evaluate an entire bus route with differing section lengths. This is defined as the ESAL impacts on any homogeneous route section multiplied by route length, which, when aggregated over the route and divided by route length, gives mean ESAL values.

However, when evaluating pavement wear, it is important to evaluate associated truck traffic volume, since buses share city streets with trucks that also contribute to pavement consumption. There are relatively few large trucks (defined as three or more axles) on Austin city streets. Using vehicle classification and registration data (*9*), the percentage of trucks in Austin ADT is estimated as 1 percent for arterial streets, 0.8 percent for collector streets, and 0.6 percent for residential streets. The reason for Austin's low percentage of trucks is that the city is essentially a university community and has no heavy industries or significant commercial sectors that require heavy truck operations.

One characteristic of the Austin bus transit system is that routes often share major streets in the downtown area. For instance, as many as 14 bus routes share a section of 11th Street in central Austin. Additionally, bus numbers may differ depending on their direction of travel on the same street, which complicates bus ESAL computations.

Three major bus routes, reflecting a range of pavement types, were chosen for the study analysis. All routes are operated with GILLIG 1100 diesel buses, and are as follows:

- *IF route (university shuttle bus),* with a length of about 4.8 km (3.0 mi). The bus runs every 4 or 6 min throughout the day, with 158 total repetitions in a weekday.

- *FW bus route (university shuttle bus),* with a length of about 7.36 km (4.6 mi) excluding the freeway segment. The bus runs every 6 to 8 min most of the day, with about 105 repetitions in a weekday.
- *No. 1 bus route (Metro bus),* with a length of about 15 km (9.5 mi). The bus runs every 10 min, with 84 repetitions during a weekday.

The key routes were then broken down into homogeneous sections with respect to pavement type and design. Under the CNG bus application, and in normal traffic, the ESAL increase among sections of the IF bus route ranges from 3.5 to 8.0 percent; over the entire IF bus route it averages 6.1 percent. The ESAL increase among sections of the FW bus route ranges between 2.7 and 9.3 percent, and for the entire FW bus route averages 7.3 percent. The ESAL increase among sections of the No. 1 bus route lies between 1.6 and 34.5 percent, and for the entire No. 1 bus route the average is 10.9 percent.

The entire route system is estimated at about 1536 lane-km (960 lane-mi) of the total 8000 lane-km (5,000 lane-mi) streets, and the percentage increase of ESAL estimated under CNG bus application is 6.7 percent. This number is based on buses alone. If trucks on bus routes were 15 percent of total ESALs, the predicted ESAL increase would fall to 5.7 percent rather than 6.7 percent. If the pavement has a 20-year design life, the service life reduction under an increase of 6 percent ESAL application is estimated as slightly over 1 year.

STREET REHABILITATION

The three routes were also used to estimate the rehabilitation cost (R-cost). A pavement rehabilitation model, Municipal Pavement Rehabilitation Design System Version 1.0, was used to determine these effects. First developed by ARE Engineering Consultants, Austin, Texas, and applied in the city of Austin, the model considers pavement condition and remaining life, structure and material properties, traffic parameters, and construction unit costs within a life-cycle cost analysis framework (*10*). Impacts are evaluated by reporting the percentage increase of overlay rehabilitation cost, and results based on a 20-year design period are given in Tables 3 and 4, which examine the IF and FW routes. The remaining life percentage (RL), a model input, is estimated on three indexes: surface distress index (SDI), riding comfort index (RCI), and pavement quality index (PQI)—each taken from the data base of the Street and Bridge Division of the city of Austin and information from a study in Alberta (*11*). The maximum and minimum values for the three indexes are SDI (10, 3.5), RCI (10, 5.5), and PQI (10, 4.7), and any index can be used to determine the remaining life of a pavement. Using PQI, for example:

$$RL_{estimate}\ \% = (PQI_{to\ date} - PQI_{min})/(PQI_{max} - PQI_{min}) \times 100 \qquad (1)$$

In this paper, a combination of the three indexes is used. First, RL is calculated from each index in the manner described, and the three RL calculations are combined to form a single value using weights of 0.6 for SDI and 0.2 for RCI and PQI. The date when the pavement was last improved is used as a base, and the RL is calculated as a percentage and rounded to 5 percent increments. The structure types and financial data are based on street category and cost information obtained from the Street and Bridge Division of the city of Austin (*12*). In addition, the traffic growth rate is estimated as 1 percent, on the basis of the projection of population growth and truck registration data (*13*).

These tables show that the average R-cost increment weighted for the IF bus route is 6.2 percent, which equates to $1.39/yd^2 weighted by section length. The range of R-cost increment for sections of the IF route is 2.1 to 13.4 percent.

The No. 1 bus route has a weighted average cost increment of 5 percent, which is equivalent to $1.33/yd^2. For sections of the FW route, the range of cost increment of sections in this route is from 0 to 18.6 percent.

TABLE 3 Rehabilitation (Overlay) Cost Comparison for IF Bus Route

Section Number	Structure Type Index	Remaining Life (RL) (%)	Cumulated ESAL W/Diesel bus application	Cumulated ESAL W/CNG bus application	ESAL Increase (%)	Cost ($/SY) under Diesel bus application	Cost ($/SY) under CNG bus application	Cost Increase (%)
1	2	20	1997000	2075000	3.9	28.31	28.9	2.1
2	2	70	2125000	2210000	4.0	8.52	9.06	6.3
3	1	30	2032000	2116000	4.1	18.57	18.99	2.3
4	1	20	2044000	2129000	4.2	21.22	21.84	2.9
5	2	35	2493000	2692000	8.0	30.42	32.37	6.4
6	2	35	2723000	2931000	7.6	33.41	35.33	5.7
7	2	60	2950000	3166000	7.3	16.64	18.45	10.9
8	2	60	3249000	3482000	7.2	18.67	20.07	7.5
9	2	60	3255000	3489000	7.2	19.21	20.1	4.6
10	2	20	3255000	3489000	7.2	44.13	47.19	6.9
11	2	70	3255000	3489000	7.2	19.89	22.56	13.4
13	2	15	3102000	3211000	3.5	34.3	35.19	2.6

Section 12 on 26th street is excluded from these calculations because it was just reconstructed in 1993.

TABLE 4 Rehabilitation (Overlay) Cost Comparison for FW Bus Route

Section Number	Structure Type Index	Remain Life (RL) (%)	Cumulated ESAL W/Diesel bus application	Cumulated ESAL W/CNG bus application	ESAL Increase (%)	Cost ($/SY) under Diesel bus application	Cost ($/SY) under CNG bus application	Cost Increase (%)
1	2	65	1399000	1455000	4.0	3.82	4.36	14.1
2a	2	25	1394000	1451000	4.1	15.44	15.99	3.6
2b	2	60	1394000	1451000	4.1	5.54	6.07	9.6
3	2	40	1633000	1779000	8.9	13.36	14.67	9.8
4	2	65	1657000	1804000	8.9	6.97	8.16	17.1
5	3	70	2415000	2480000	2.7	13.43	13.77	2.5
6a	3	55	3327000	3610000	8.5	22.94	24.42	6.5
6b	3	80	3327000	3610000	8.5	20.58	21.92	6.5
7	3	50	2793000	2991000	7.1	16.93	17.78	5.0
8	3	30	4087000	4345000	6.3	30.11	31.04	3.1
9	3	30	4333000	4672000	7.8	37.17	39.22	5.5
10	3	40	4350000	4692000	7.9	37.32	38.55	3.3
11	3	40	4694000	5037000	7.3	38.6	40.27	4.3
13	2	40	1532000	1594000	4.0	12.1	12.68	4.8
14	2	20	1532000	1594000	4.0	27.71	28.22	1.8

Section 12 on 26th street is excluded from these calculations because it was just reconstructed in 1993.

Since each section is an independent overlay design case, 45 design sections of the three pilot routes were considered to represent the whole route system. An estimate for a bus route was determined from the following:

$$\begin{aligned}&\text{Rehabilitation (overlay) cost increase (\%)}\\&= 3.2598 + 0.4595 \times [\text{ESAL increase (\%)}]\\&\quad + 0.0444 \times [\text{RL (\%)}] - 1.5177\\&\quad \times (\text{index number of structure type}) \qquad (2)\end{aligned}$$

where there are three structural types: Type 1, with an asphalt concrete surface layer of 7.6 cm (3 in.) and a base layer of 15.24 cm (6 in.); Type 2, with an asphalt concrete surface layer of 7.6 cm (3 in.) and a 25.4-cm (10-in.) base layer; and Type 3, with a 7.6-cm (3-in.) surface layer and a 30.48-cm (12-in.) base layer.

The data for remaining life and percentage ESAL increases were determined from the Austin city data base and study analysis, respectively, and are reported elsewhere, along with evaluations of other routes (*1*).

Additionally, the mean of the sample statistic RL is 45.2 percent, with a standard deviation of 19.8 percent. The mean of the ESAL percentage increase of the sample statistic is 9.6 percent, with a standard deviation of 8.9 percent, and the mean of the R-cost percentage increase of the sample statistic is 5.8 percent, with a standard deviation of 4.3 percent (*1*).

CONCLUSIONS

New technologies are increasingly being evaluated using systems processes for which all costs are identified and subjected to economic review. In this light, alternative fuels such as CNG should be subject to a full cost-benefit analysis, including pavement and the environmental impacts generally treated as externalities. Therefore, the traditional analysis of agency and vehicle cost trade-offs would be enhanced by the inclusion of safety, air quality, noise, and other impacts.

Addressing pavement issues, which are often ignored in alternative fuel analyses, current CNG systems raise the weight of transit buses and may impose additional stresses on route pavements. Accordingly, the impact of this marginal cost should be determined and included in any evaluation should it prove to be significant. Extrapolating the results of the sampled routes to the bus transit network in Austin, it is predicted that totally replacing diesel fuel with CNG stored in aluminum storage cylinders across the entire bus fleet would raise ESAL impacts by about 6 percent. If Austin had a more industrialized sector, the resulting truck traffic would cause the CNG bus impact to fall to around 4 percent.

Translating these impacts into rehabilitation costs, the Austin system under CNG bus transit operations would generate an additional overlay rehabilitation cost estimated at between 4 and 5 percent, slightly less than the rate of ESAL increase. Last year, the city of

Austin spent more than $75 million on rehabilitating bus routes, a figure that suggests the scale of potential CNG bus operations on the city's maintenance budget. Since these are nontrivial, it suggests that pavement impacts are a legitimate element to be evaluated in a full cost-benefit analysis of alternative fuel use for transit bus operations.

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