Southwest Region University Transportation Center

Impact of Compressed Natural Gas Fueled Buses on Street Pavements

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16. Abstract

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Capital Metro, the Austin, Texas transit authority, is currently evaluating a number of CNG fueled buses. As part of the U.S. DOT Region Six University Transportation Centers Program (UTCP), a study was instigated into the scale of incremental pavement consumption associated with the operation of these buses. The study suggests that replacing current vehicles with CNG powered models utilizing aluminum storage tanks would raise average network equivalent single rehabilitation costs across the network of over four percent. Finally, it recommends that full cost study be undertaken with evaluation of the adoption of alternative bus fuels - which includes pavement and environmental impacts.

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IMPACT OF COMPRESSED NATURAL GAS FUELED BUSES ON STREET PAVEMENTS

by

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and
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Research Report SWUTC/95/721913-1

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EXECUTIVE SUMMARY

Federal Clean Air Act Amendments of 1990 (CAAA) and the Energy Policy Act of 1992 (EPACT), together with other state regulations have encouraged or mandated transit systems to use alternative fuels to power bus fleets. Among such fuels, compressed natural gas (CNG) is attractive, although it must be stored in robust, heavy pressurized cylinders, capable of withstanding pressures up to 5,000 psi. Such systems are typically heavier than conventional diesel storage tanks. As a result, this raises gross vehicle weight, sometimes significantly, which then increases the consumption of the pavement over which CNG buses operate.

New technologies are increasingly being evaluated in systems in a manner where all costs are identified and subjected to economic review. In this light, alternative fuels such as CNG should also be subject to a full cost-benefit analysis, including pavement and environmental impacts which are sometimes treated as externalities. Addressing pavement issues, current CNG systems raise the weight of transit buses and may therefore impose additional stresses on route pavements, and accordingly, the impact of this marginal cost should be determined and included in any evaluation.

Extrapolating the results from the sampled routes over 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 six percent. If Austin had a more industrialized sector, the resulting truck traffic would have caused the CNG bus impact to fall to around four 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 four and five percent, slightly less than the rate of ESAL increase. In 1994, the City of Austin spent over $75 million on bus route rehabilitation which gives an idea of the scale of potential CNG bus operations on the city's maintenance budget. Since these are non-trivial, it suggests that pavement impacts are a legitimate cost element to be evaluated in a full cost-benefit evaluation of alternative fuel use in transit bus operations.

ABSTRACT

Federal Clean Air Act Amendments of 1990 (CAAA) and the Energy Policy Act of 1992 (EPACT), together with other state regulations have encouraged or mandated transit systems to use alternative fuels to power bus fleets. Among such fuels, compressed natural gas (CNG) is attractive, although it must be stored in robust, heavy pressurized cylinders, capable of withstanding pressures up to 5,000 psi. Such systems are typically heavier than conventional diesel storage tanks. As a result, this raises gross vehicle weight, sometimes significantly, which then increases the consumption of the pavement over which CNG buses operate.

Capital Metro, the Austin, Texas transit authority, is currently evaluating a number of CNG fueled buses. As part of the U.S. DOT Region Six University Transportation Centers Program (UTCP), a study was instigated into the scale of incremental pavement consumption associated with the operation of these buses. The study suggests that replacing current vehicles with CNG powered models utilizing aluminum storage tanks would raise average network equivalent single axle (ESAL) impacts by around six percent. This translates into an increase in total annual overlay rehabilitation costs across the network of over four percent. Finally, it recommends that a full cost study be undertaken with evaluating the adoption of alternative bus fuels - which includes pavement and environmental impacts.

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CHAPTER 1. INTRODUCTION

OVERVIEW

Natural gas has been used as a motor fuel for more than 100 years. Compressed natural gas (CNG), which is natural gas compressed under 2,400 psi to 3,600 psi, has been used as an engine fuel in light and medium-duty utility fleet vehicles and stationary applications since World War II (Ref 1). During the 1973 Arab oil embargo, many utility fleets converted to CNG fuel use. As oil prices declined, consumers returned to their regular usage of gasoline and diesel and the growth in CNG fuel declined. In recent years, however, efforts have been made to improve urban air quality. Such efforts are embodied in legislation including the federal Clean Air Act Amendments of 1990 (CAAA) (Ref 2). As a result of the CAAA, transit authorities across the country have begun evaluating the use of clean alternative fuels, and CNG fuel has regained public attention.

In their efforts to improve usage of CNG fuel, researchers and engineers across the country have made great improvements in both the technology and cost efficiency of these fuels. Despite these developments, the impact of using CNG has not been fully evaluated. One element which has not been studied is the effect on pavements of CNG fueled vehicles operating on city roadways. Ensuing costs may include increase in deterioration of street pavements as well as the cost of pavement rehabilitation. As buses are affected by the CAAA, the impact of using CNG is of concern both to city transportation planners and pavement engineers.

The fundamental differences between CNG fuel and diesel fuel are the methods of storing the fuels and the type of storage facility required. CNG is gaseous and must be compressed and stored in heavy pressurized cylinders, capable of withstanding pressures of more than 5,000 psi. In addition, since energy density (an index which indicates the amount of energy that can be generated from a unit volume of fuel) of CNG is only 28 percent of that of gasoline or 25 percent of that of diesel fuel, CNG fueled vehicles must typically carry a number of such tanks. Consequently, CNG fueled vehicles are heavier than their conventional counterparts. For buses, this weight increase is particularly significant. Most diesel buses already have single axle loads over 18,000 lbs, thus even a small additional weight will cause a significant increase in pavement design loads and accelerate the wear of street pavements. As buses are the major source of damage to pavements on their routes, this is a negative factor for CNG fuel. For comprehensive understanding, however, all aspects of converting to CNG use in city buses should be considered.

OBJECTIVE AND SCOPE OF THIS STUDY

The objective of this study is to estimate increased damage to street pavements of heavier CNG fueled buses and to evaluate the impact of CNG buses on pavement rehabilitation costs. Study results can provide opportunities for urban transportation planners to evaluate such impacts objectively.

The scope of this study includes an investigation and analysis of CNG fuel tankage and its impact on bus weight, the characteristics of passenger loading and its correlation with bus axle loads, and associated traffic on bus routes in Austin, Texas. Impacts of CNG bus operations on pavement damage and pavement rehabilitation costs are estimated based on the findings.

This study is based on CNG bus use in the City of Austin, comparing CNG and diesel buses operated over the Capital Metro bus route system.

ORGANIZATION

Chapter 1 introduces the intentions, objectives, and scope of the study.

Chapter 2 presents background review on CNG uses. The public laws regarding clean alternative fuels are briefly enumerated.

Chapter 3 presents basic knowledge about CNG fuel and the characteristics of its fuel tankage.

Chapter 4 presents characteristics of bus loading, including the trend of passenger occupancy, the distribution of passenger loading, and the relationship between occupancy and bus axle loads.

Chapter 5 presents the axle loads of buses in operation on the streets of the City of Austin.

Chapter 6 presents a study on vehicle classification on city streets, including the volume and the growth rate of truck traffic associated with buses.

Chapter 7 presents a study of the impact of CNG buses on pavement damage. CNG fueled buses are compared with diesel buses on four pilot routes. Two terms, the ESAL-lane-mile and the weighted mean ESAL, are defined.

Chapter 8 presents estimates of the impact of CNG bus operation on the cost of pavement rehabilitation based on the study of the three pilot routes. Costs of pavement rehabilitation of CNG bus operation and diesel bus operation are then compared and the percent increase estimated. Finally, an estimation model and four estimation charts are given.

Chapter 9 presents both a synthesis and discussion of major findings and interesting points of this study.

Chapter 10 presents conclusions and recommendations of this study.

CHAPTER 2. BACKGROUND REVIEW

BACKGROUND OF CNG USE

The United States has depended on foreign oil for more than two decades. In 1990, while the world was consuming a total of 65.9 million barrels per day, 7.6 million barrels were shipped to the U.S. This made up 11.5 percent of the world's daily petroleum consumption and 47 percent of the total U.S. petroleum consumption (Ref 3). Now almost half of U.S. total petroleum consumption is foreign oil.

Of the petroleum consuming sectors in the U.S., transportation is the largest and is almost entirely oil dependent. More than 97 percent of transportation energy is derived from petroleum. In 1990, for example, 65 percent of the total U.S. petroleum was consumed by U.S. transportation (Ref 3), and 77 percent of this amount by U.S. highway users (Ref 4). In other words, highway users consumed 50 percent of the total petroleum used in the U.S. Although fuel consumption efficiency of vehicles has improved significantly since 1973 (the time of the Arab oil embargo), the total petroleum consumption on U.S. highways has been rising. Other oil consuming sectors such as industrial, residential and commercial sectors, as well as electric utilities, have actually reduced their oil consumption and largely switched from petroleum to natural gas over the past 20 years (Refs 3, 4).

Since it is dependent on foreign oil supplies, the U.S. has to pay the full market cost. From 1970 to 1991, net imports of crude oil and petroleum products were valued at $1071.66 billion (in 1987 dollars) (Ref 3). Some analysts believe that dependency on foreign oil supplies not only creates a monetary deficit for the U.S. but also creates "some hidden, nefarious costs as well" (Ref 5). It has been calculated that "the safeguarding of oil supplies in the Middle East and the recent Persian Gulf war conservatively added about $23.50 to the actual cost of each barrel of oil imported into the United States" (Ref 5).

Americans are accustomed to driving cars, and the growth of the number of vehicles exceeds that of the population. From 1970 to 1990, while the population increase was 21.9 percent, the increase in number of vehicles was 75 percent. Particularly in urban areas, the rapid increase in the number of vehicles has been accompanied by a worsening of air pollution. Gasoline and diesel vehicle emissions not only reduce vision and release noxious odors, but also cause severe health problems when the levels of emissions rise above the standard NAAQS (National Ambient Air Quality Standards). These levels were established by the Environmental Protection Agency on six pollutants: Pb (Lead), SO_2 (Sulfur Dioxide), NO_2 (Nitrogen Dioxide), O_3 (ozone), CO (Carbon Monoxide) and "particulate matter." The EPA reported that "... motor vehicles are the major contributors of all these pollutants with the exception of sulfur dioxide" (Ref 5). The issue of emissions and air quality has attracted public concern with a growing recognition that the likelihood of solving this problem is by clean alternative fuels.

The use of clean alternative fuels produced in the U.S., such as ethanol and natural gas, has attracted political interest at both state and federal levels. Arguing on the basis of economic gains from the adoption of such fuels, legislators have passed a number of laws related to clean alternative fuel uses. These are now reviewed in the following section.

PUBLIC LAWS REGARDING CLEAN ALTERNATIVE FUELS

Since 1988, the U.S. has put forth major efforts to solve the pressing problems of energy dependency and degradation of urban air quality. Several federal and state regulations encouraging the development and use of clean alternative fuels have been created (Ref 6). All federal legislation requires rapid response and specific deadlines for accomplishing goals. Failure to comply with the laws means loss of federal transportation funds. The following is a list of federal laws:

1) Alternative Motor Fuel Act of 1988. This law was passed to encourage the development and widespread use of alternative fuels and the production of alternative fuel vehicles.

2) Clean Air Act Amendments of 1990. These amendments essentially affect the urban areas that do not meet air quality standards. It is important in the following respects: mandating the production of clean fuel vehicles, requiring certain fleet authorities to purchase clean fuel vehicles, tightening emission standards, and requesting fuel providers to supply clean fuels. City transit buses fall under the category of fleet vehicles and must meet the clean air standard.

3) Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. This legislation affects a wide range of transportation decisions, such as designating transportation funds to be used for air quality related projects and requiring transportation plans to conform with the improvement of air quality.

4) Energy Policy Act of 1992. This Act sets specific goals for reducing petroleum consumption and mandates purchase of alternative fuel vehicles in major population centers all over the U.S.

Five "clean alternative fuels" have been recognized in state and federal legislation and regulations. These include:

1) Compressed natural gas,
2) Methanol,
3) Ethanol,

4) Propane or Liquid propane gas (LPG), and
5) Electricity.

The properties of the five alternative fuels are summarized in the FTA report entitled "Properties of Alternative Fuels" (Ref 7).

According to an American Gas Association (AGA) report, more than 20 states also passed alternative fuel legislation in 1991. The State of Texas is in the forefront of this movement. Texas was the first state to enact legislation regarding use of alternative tansportation fuels (ATF) in certain state and municipally owned fleets in 1989.

The Texas Senate has passed two bills pertaining to alternative fuel legislation since August 28, 1989. One is Senate Bill 740 (Ref 8), which creates an incentive for use of Texas natural gas and other alternative fuels in the transportation sector. The other is Senate Bill 769 (Ref 9), which empowers the Texas Air Control Board (TACB) to safeguard and improve the air quality by requiring the use of compressed natural gas or other alternative fuels in transit buses and certain local government and private fleet vehicles in areas that are in non-attainment of federal air quality standards. These two pieces of legislation require the affected entities to achieve, at minimum, the following percentages of alternative-fueled vehicles in their fleets by the following dates: 30 percent by September 1, 1994; 50 percent by September 1, 1996; and, following a decision by TACB that the program has been effective in reducing total annual emissions from vehicles in the area, 90 percent by September 1, 1998. Implementation of these laws will substantially improve air quality in Texas and provide significant benefits to the state economy.

CHAPTER 3. COMPRESSED NATURAL GAS AND TRANSIT OPERATIONS

COMPRESSED NATURAL GAS: CHARACTERISTICS

Natural gas is a global energy resource formed by geological processes and may vary in quality from field to field. The principal hydrocarbon is methane (CH_4) which accounts for about 85 to 95 percent of natural gas (Ref 6). For transportation and storage, natural gas is usually either compressed or liquefied. Gas which is compressed to pressures between 2,400 and 3,600 psi is called compressed natural gas (CNG). Gas which is liquefied by cooling to below its boiling point of about -161 ^{0}C (-270 ^{0}F) at atmospheric pressure is called liquefied natural gas (LNG). LNG must be stored in a highly insulated tank which is expensive. The energy density of LNG, however, is 2.2 times higher than that of CNG. The weight per cubic foot of natural gas is about 0.047 lb/ft^3 which is lighter than air (about 0.08 lb/ft^3). It has a higher self-ignition temperature (about 1200 ^{0}F) than gasoline (as low as 600 ^{0}F). It also has a very narrow range of flammability, which means that natural gas will never burn in concentrations in air below about five percent and above about 15 percent. These properties insure that CNG is much safer than gasoline (Ref 10). A significant disadvantage of CNG is that it has a lower energy density than diesel and gasoline. In LHV (lower heating values) measurements, the energy density of diesel fuel is 129,400 Btu/gal while that of CNG, compressed at 2,400 psi and 70 ^{0}F, is only 19,760 Btu/gal. If CNG is compressed at 3,000 psi, the energy density will rise but will still be only one-fifth that of diesel fuel (Ref 11).

Natural gas has a long history of applications. In 206 B.C., China used natural gas to heat salty water to evaporate the salt (Ref 12). Romans and Greeks are supposed to have known of the gas before the birth of Christ, but its initial use was to create flames for religious purposes. Few records exist of other uses until the 17th century, when evidence indicates that natural gas was used for heating and lighting in northern Italy. In 1821, natural gas was discovered in Fredonia, New York. It was piped from a 27-ft-deep well to nearby houses for lighting. In the later 1800's, knowledge of natural gas grew rapidly but its application was still limited. At the same time, oil was much easier to transport and store. Consequently, in the 1920's and early 1930's, attention was paid to searching and drilling for oil, and natural gas was only an unusable by-product. Some was piped for local use, but most was simply released into the air or flared. One estimate says that up to the late 1940's, wasted natural gas (lost into air or flared) in the U.S. was as high as 76 trillion cubic feet. In the 1950's, pipeline systems progressed significantly and by 1966, natural gas became available by pipeline for the continental

U.S. Today, the U.S. has a total of about 1,100,000 miles of pipeline, the most extensive gas pipeline system in the world (Ref 5).

The first practical four-cycle engine run on natural gas was invented by the German inventor Nicholas Otto in 1876, nine years before Karl Benz built the first internal combustion engine powered vehicle. For the past 100 years, people have successfully converted almost every type of vehicle to run on natural gas. But, for cost-related reasons, auto manufacturers worldwide have declined to build vehicles operated on natural gas, and in the U.S. almost all vehicles are oil-dependent. In spite of this, however, natural gas fueled vehicles (NGVs) do exist worldwide. For example, Italy has been using NGV's since 1940 and has the largest number in the world, estimated at 300,000 units (Refs 5, 13).

Under the legislation described in the previous section, natural gas has, at last, arrived on center stage. By February 1993, approximately 600 public and private natural gas refueling stations were in operation nationwide, and new refueling stations were opening at a rate of three to four a week. It was also estimated that approximately 30,000 to 50,000 of the nation's more than 190 million vehicles were equipped to run on CNG (Ref 14).

COMPRESSED NATURAL GAS: ADVANTAGES AS A TRANSIT FUEL

The major advantages of CNG can be summarized by the following characteristics (Refs 1,3,15,16):

1) Cleanliness — CNG contains no particulate. It provides dramatic reductions of 85 to 99 percent of CO and HCs (reactive hydrocarbons), and up to a 65 percent reduction of nitrogen oxides as compared with diesel fuel.

2) Safety — CNG is neither corrosive nor toxic. Since it is lighter than air, it dissipates if released. The American Gas Association Monthly (January 1981) reported that CNG has been used in Italy for 30 to 40 years, and no deaths or injuries have been attributed to its use.

3) Abundance — Natural gas is called a domestic fuel because it is produced and supplied in the United States. The U.S. natural gas reserves on January 1, 1991 were 169.3 trillion cubic feet while crude oil reserves were 26.3 billion barrels. Using energy equivalency (1 barrel crude oil = 5.6×10^3 cubic feet natural gas), the natural gas reserve is 15 percent more than that of crude oil in the United States. According

to the U.S. Department of Energy, the lower 48 states currently have a 60 year supply of natural gas.

4) Affordability — On average, the selling price of CNG is 70 cents per equivalent gallon of gasoline. The equivalent gallon of gasoline is a commonly used term for measuring amounts of CNG.

5) Reliability — It is compatible with internal combustion systems and may extend engine life.

Developing uses of CNG fuel is an important issue to the State of Texas. Statistics show that Texas has the largest natural gas reserves in the U.S., an estimated 22 percent of the total U.S. reserve (Ref 4). Using CNG fuel will significantly benefit the Texas economy. Research has reported that production of 1 trillion cubic feet of CNG means 50,000 jobs to Texas workers, $1 billion in state revenues, and $3 billion gross state products (Ref 17).

COMPRESSED NATURAL GAS: TRANSIT VEHICLE STORAGE

There are two fundamental differences between CNG fuel and conventional fuels. First, CNG is in gaseous form rather than liquid; second, the energy density (Btu/gal) of CNG is much lower than that of diesel fuel or gasoline. These characteristics make the onroad fuel tankage of CNG vehicles totally different from that of the conventional vehicles. Tanks of CNG fuel are pressurized cylinders capable of holding CNG at 3,000 to 3,500 psi working pressure. In addition, fuel lines between cylinders, pressure regulator, and the refueling valve are designed to maintain pressure up to four times the working pressure, thus, they are much stronger than their gasoline counterparts (Ref 16). As a result of these differences, the weight of a CNG vehicle is significantly increased. The increased weight not only reduces vehicle performance, but also increases pavement damage.

Since gas can expand uniformly within the boundaries of an enclosing container, it can be compressed in any container shape. From a mechanical perspective, the best container for a high pressure gas is a sphere. However, a spherical tank is not practical for vehicles and the next best shape is an cylinder with hemispherical ends. Cylinders can be made from steel, steel composite, or aluminum composite. To meet CNG fuel tank standards, cylinders are built to withstand four times the design working pressure and are submitted to a hydrostatic test at approximately 1.5 times the design working pressure periodically (aluminum and steel composite cylinders are tested every three years).

Since this weight increase due to CNG tankage is on bus unladen weight, CNG bus manufacturers actually prefer to use composite-reinforced aluminum cylinders which are about 50 percent lighter than steel cylinders (Ref 18), even though it may cost more money. Table 3.1 shows the size, weights, and capacities of composite-reinforced aluminum CNG fuel cylinders.

TABLE 3.1 SIZES, WEIGHTS & CAPACITIES OF COMPOSITE-REINFORCED ALUMINUM CNG FUEL CYLINDERS (REFER TO FIGURE 3.1)

Cylinder Size B x A	Water Capacity	Cylinder Weight	Natural Gas Capacity	Gasoline Equivalency
in.	Liters	lbs	SCF*	U.S. Gal
10 x 35	31.6	54.9	288	2.7
10 x 42	39.4	66.5	359	3.4
10 x 50	48.1	80.1	438	4.0
10 x 60	59.0	96.3	538	5.0
10 x 72	71.3	116.2	649	6.1
13 x 35	50.8	89.0	462	4.3
13 x 42	63.9	107.0	582	5.4
13 x 50	74.4	128.2	714	6.6
13 x 60	97.3	154.5	886	8.3
13 x 72	121.0	193.3	1102	10.3
13 x 84	147.5	224.0	1303	12.2

Notes:
1) Source from CNG Cylinder Company of North America, Long Beach, CA. (Ref 18).
2) * SCF is the standard cubic feet. Number of SCF means the cylinder is capable of containing such amounts of natural gas at pressure 3,000 psi and temperature 70 ^{0}F.
3) Equivalency based on 107 SCF natural gas = 1 U.S. gal. of gasoline.

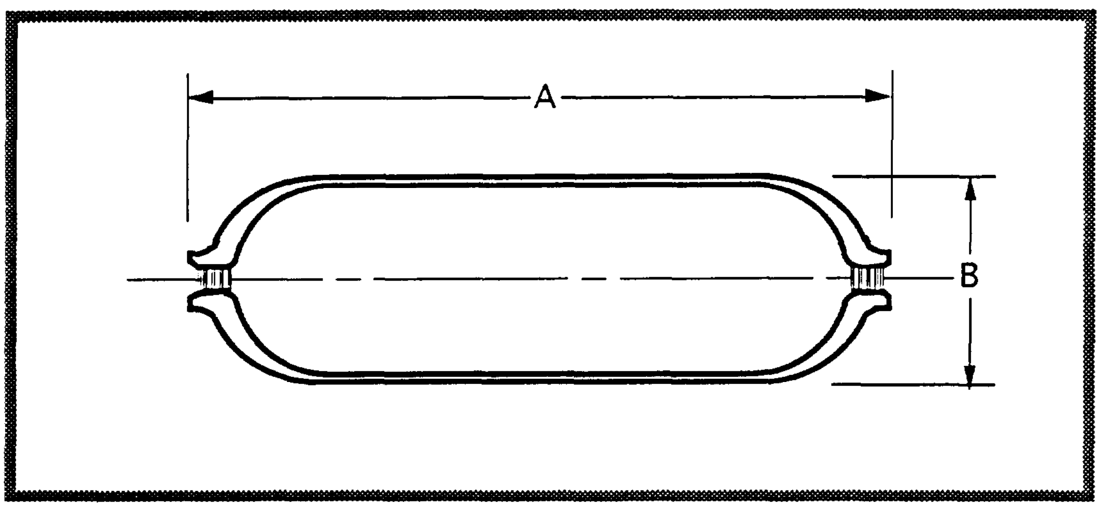


Fig 3.1 High pressure cylinder used as CNG fuel tank

Usually the capacity of a cylinder is expressed in liters of water, and one water liter of cylinder capacity can contain 0.36 lbs natural gas at standard working pressure of 3,000 psi and temperature of 70 ^{0}F (Ref 16). Using this norm, we show the capacity in pounds of natural gas and the ratio of the weight (cylinder + CNG fuel) to the equivalent gasoline gallons in Table 3.2.

TABLE 3.2 RATIO OF "WT. OF (CYLINDER+CNG FUEL)" TO EQUIVALENT GASOLINE GALLON

Size B x A	Water capacity	Natural Gas Capacity	Weight of (Cylinder + CNG)	Ratio of the Weight of (Cylinder+CNG fuel) to the Equivalent Gasoline Gallon
Inches	Liters	Lbs	Lbs	Lbs/Gal.
10 x 35	31.6	11.4	66.3	24.5
10 x 42	39.4	14.2	80.7	23.7
10 x 50	48.1	17.3	97.4	24.4
10 x 60	59.0	21.2	117.5	23.5
10 x 72	71.3	25.7	141.9	23.3
13 x 35	50.8	18.3	107.3	25.0
13 x 42	63.9	23.0	130.0	24.1
13 x 50	74.4	26.8	155.0	23.5
13 x 60	97.3	35.0	189.5	22.8
13 x 72	121.0	43.6	236.9	23.0
13 x 84	147.5	53.1	277.1	22.7
			Average :	**23.68**

Note: Numbers in this table refer to Table 3.1.

The average ratio of the weight of (Cylinder + CNG Fuel) to the Equivalent Gasoline Gallon is 23.68 lbs/gal. For conventional diesel fuel tanks, the ratio of the weight of (tank + diesel fuel) to the gallons of diesel is 10.46 lbs/gal (Ref 19). If the small difference between diesel fuel and gasoline is ignored, then, in order to achieve fuel equivalency, vehicles are required to carry additional weight of CNG fuel tankage of (23.68 - 10.64) = 13.04 ≈ 13 lbs for each equivalent gasoline gallon of CNG fuel.

Considering the support structures for holding the extra weight of a heavy fuel cylinder, this number should be further multiplied by a factor greater than 1.0. In addition, this extra weight will eventually reduce the vehicle performance. To achieve equivalent performance and mileage range, horsepower must be increased, so more fuel is required. A U.S. Environmental Protection Agency study indicated that the weight increase would be compounded by a factor of approximately 1.3 to account for the necessary modifications (Ref 11). If a diesel bus weighed

28,000 lbs with fuel capacity of 120 gallons, a CNG bus would be required to carry an additional weight of fuel tankage of

$$120 \text{ (gal)} \times 13 \text{ (lbs/gal)} \times 1.3 = 2028 \text{ lbs}$$

in order to achieve equivalent mile range and performance, a 7.2 percent weight increase. For city transit buses, any weight increase has a major impact on pavement design and performance, because most standard diesel buses have single rear axle loads greater than 18,000 lbs.

The equivalent 18-kip single-axle load, or ESAL, is a load equivalency widely used in designing pavement structures and predicting the loss of pavement serviceability. The equivalency concept was developed from the results of the AASHO road test (1958-1961) (Ref 20) Under this concept, the random mixture of vehicles with various axle loads and number of axles that constitute normal traffic can be converted to a number of 18-kip single-axle load, which has an equivalent effect on pavement performance. By this conversion, ESAL is about the fourth-power of the ratio of the converted single-axle load to the 18-kip single-axle load. Therefore, a small increase of a single-axle load over 18,000 lbs will result in a sharp increase of ESALs, evidence of the significance of increasing the bus weight to street pavements. The ESAL will be further explained later and the conversion equation for ESAL will be shown in Chapter 5.

COMPRESSED NATURAL GAS: BUS DESIGNS

A CNG fueled bus appears the same as a conventional diesel bus, rides comfortably, and operates like a conventional diesel bus as far as the passengers are concerned. It may carry signs that say "powered by clean natural gas" or "environment protection." On acceleration, the bus exhaust contains no black smoke.

While the engine may be built especially for CNG fuel, it may also be for both CNG and diesel. Usually, CNG fuel cylinders are mounted under the bus floor, but cylinders can also be mounted on the bus roof. Despite similarities in appearance and comfort, the fuel systems are totally different. Figure 3.2 is a sketch of a TMC CNG bus and its fuel system. TMC CNG buses are produced by the Transportation Manufacturing Corporation (TMC), Roswell, New Mexico. By the end of 1993, TMC had delivered 30 CNG fueled buses (40 feet long with 43 seats) to Capital Metro in Austin. TMC utilizes aluminum CNG fuel cylinders manufactured by CNG Cylinder Corporation of America. As many as 12 CNG fuel cylinders can be mounted under the bus floor in three bays. Since space is needed for locating the cylinders, the wheelbase of the 40 ft long TMC CNG bus is relatively longer than the GILLIG 1100, the major diesel bus used in Austin.

Another type of bus is the Blue Bird CNG bus produced by Blue Bird Cooperation, Fort Valley, Georgia. Figure 3.3 shows a chassis of a Blue Bird CNG bus in which six CNG fuel cylinders are compactly mounted longitudinally on both sides of the chassis. The cylinders are fiberglass reinforced steel produced by Pressed Steel Tank Co., Inc. The Blue Bird CNG bus is not much heavier than its diesel counterparts because it was developed for school bus operations and is inherently lighter than typical diesel transit buses. It is currently operated on a special service route as student commuter transit for The University of Texas at Austin.

Several other important bus manufactories are also producing CNG fueled buses, such as The Flxible Corporation, Delaware, Ohio, which produces Flxible Metro CNG buses of 30, 35, and 40 feet in length; Bus Industries of America Inc., Oriskany, New York, producing the Orion V/CNG, a 40 foot bus; and Nioplan USA Corp., Lamar, Colorado. These buses will not be discussed here or involved in the study since they have never been used by Capital Metro.

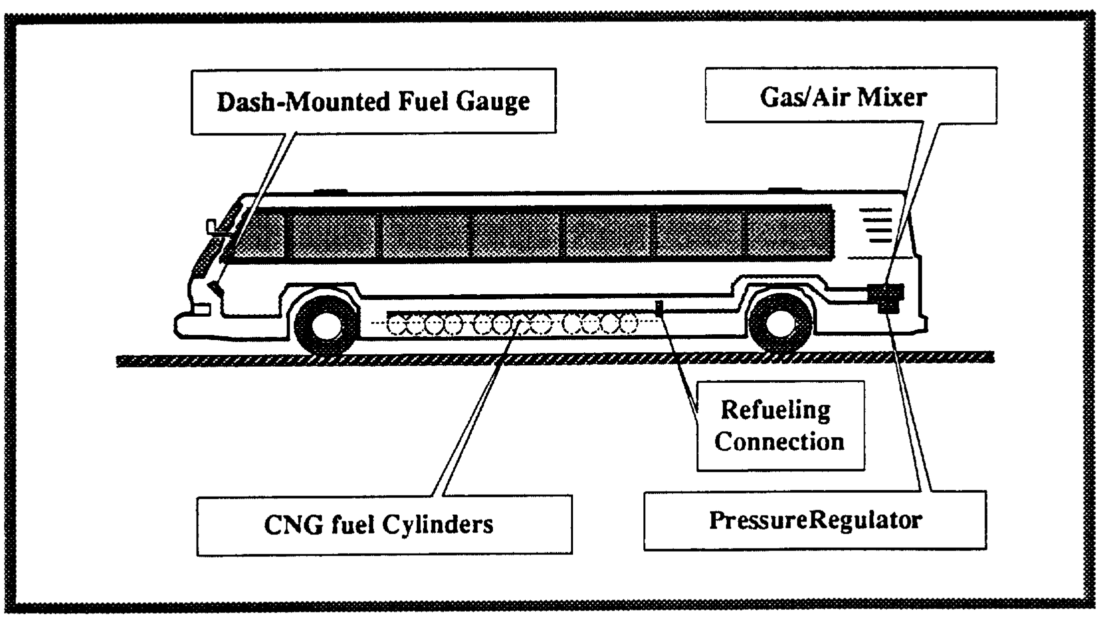


Fig 3.2 Sketch of TMC CNG bus and the fuel system (cylinder under floor)

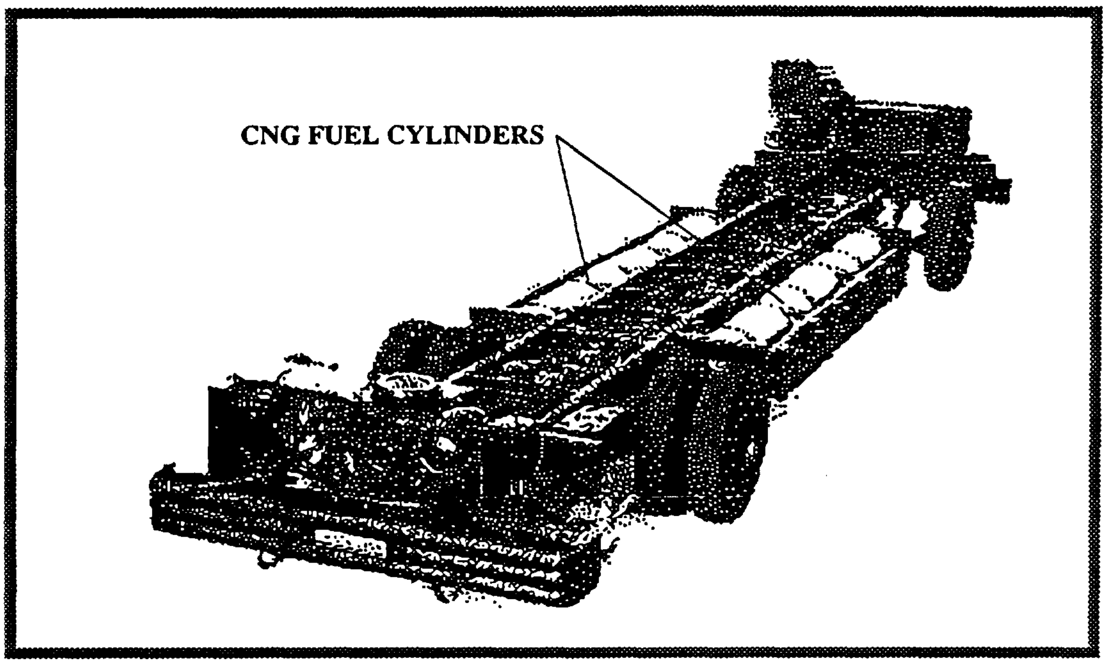


Fig 3.3 Chassis of Blue Bird CNG bus with CNG fuel cylinders (Ref 21)

It should be pointed out that the buses discussed above are all CNG fuel dedicated buses. Based on the available technology, a conventional diesel bus can also be converted to use both CNG fuel and diesel fuel. Problems associated with dual-fuel conversion such as financial costs, reliability concerns, and the need for skilled technical staff may outweigh the benefits of lower fuel costs, thus discouraging transit authorities from adopting the dual-fuel strategy. Capital Metro (Austin), Dallas Area Rapid Transit (DART), and VIA Metropolitan Transit (San Antonio) are several of many transit authorities in Texas that have no plan for converting diesel buses.

CHAPTER 4. CHARACTERISTICS OF BUS LOADING

Since moving people is the essential purpose of transit buses, passenger loading is the only payload on buses. In fact, passenger occupancy has a significant influence on the value of axle loads of buses and the related consumption of route pavement.

INTRODUCTION

Passenger loading is a moving load on buses, meaning that the value of passenger loading not only varies from time to time but also changes its center of gravity, which may be found at any point between the two axles of the bus. However, study observations show that passenger loading tends to evenly spread over the entire seating area of the bus. Based on this phenomenon, the center of gravity of passenger loading can be assumed at the geometric center of the seating area of the bus, and the contribution of passenger loading to both axles can be determined in terms of the force equilibrium.

Surveys conducted as part of this study show that the passenger occupancy varies from one stop to another along a bus route. For certain bus routes, patterns or trends of passenger occupancy along the routes can be shown. Bus routes may have different patterns or trends of passenger occupancy because the areas that each bus route passes through have different abilities to attract and generate passenger trips.

In addition, study surveys show that passenger occupancy is a stochastic variable and changes not only by stops, but also by time, even at exactly the same time of each weekday on the same bus route. It is also different from season to season, such as school semester and summer vacation. Since occupancy surveys, even for a short time, require substantial work, occupancy data are accordingly limited. Thus, the exact mean of the passenger occupancy cannot be determined. However, the range of passenger occupancy for buses is not large due to the limited seating capacity on buses, which is up to 50 for standard buses. Thus, limited survey data can be used to estimate an average passenger occupancy which is used for bus ESAL calculation.

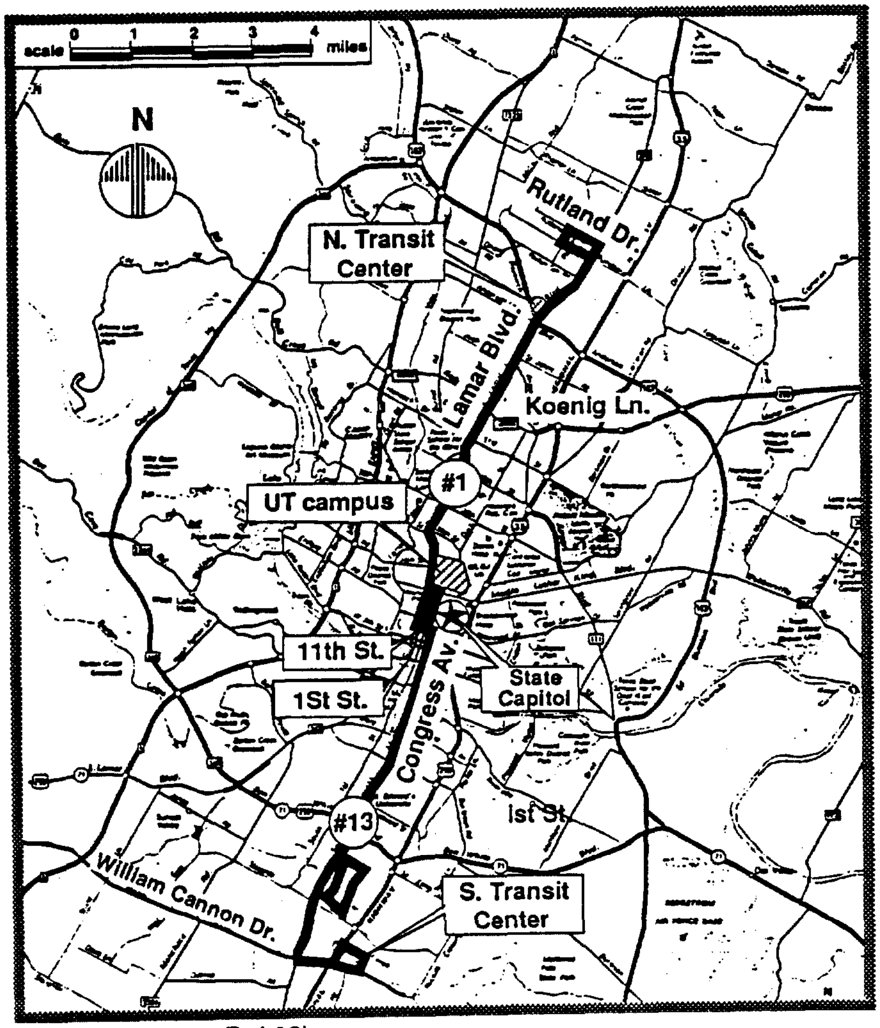
PASSENGER OCCUPANCY: PATTERNS AND TRENDS

Passenger occupancy changes along bus routes since boarding or deboarding activities vary at each bus stop. Results of repeated surveys of this study, however, show that there is a pattern of passenger occupancy for each bus route. This means that some sections of a bus route always have buses with highest occupancy. For example, sections in downtown Austin or near the campus of The University of Texas are sections of high passenger occupancy, whereas sections that are distant from the city have low occupancy. Some areas generate more passengers due to higher residential density, while others, such as the downtown district, attract more passengers due to a high level of activity during bus operations.

Surveys were conducted as part of this study on the #1/#13 Capital Metro bus route. The #1/#13 is a continuous line, numbered #1 and #13 for its north half and south half, respectively. Figure 4.1 shows a map of #1/#13 bus route, which starts from Rutland/N. Lamar in North Austin and ends at two terminals: Sheraton/S. Congress and William Cannon/S. Transit Center in South Austin.

Occupancy surveys took place at different time schedules, such as morning peak hours, off-peak hours, and evening hours. The surveyor recorded the number of passengers on the bus as the bus passed through each stop or street section. The results of the occupancy observations are shown in Figure's 4.2 and 4.3. Figure 4.2 shows the observations taken from Rutland to Sheraton (north-to-south service) while Figure 4.3 observes south-to-north.[1]

[1] Surveys 1 and 2 were proveded by Ms. Supriya Mandava, graduate engineering student at UT-Austin.



(Map source, Ref 22)

Fig 4.1 #1/#13 Bus Route of Austin Capital Metro

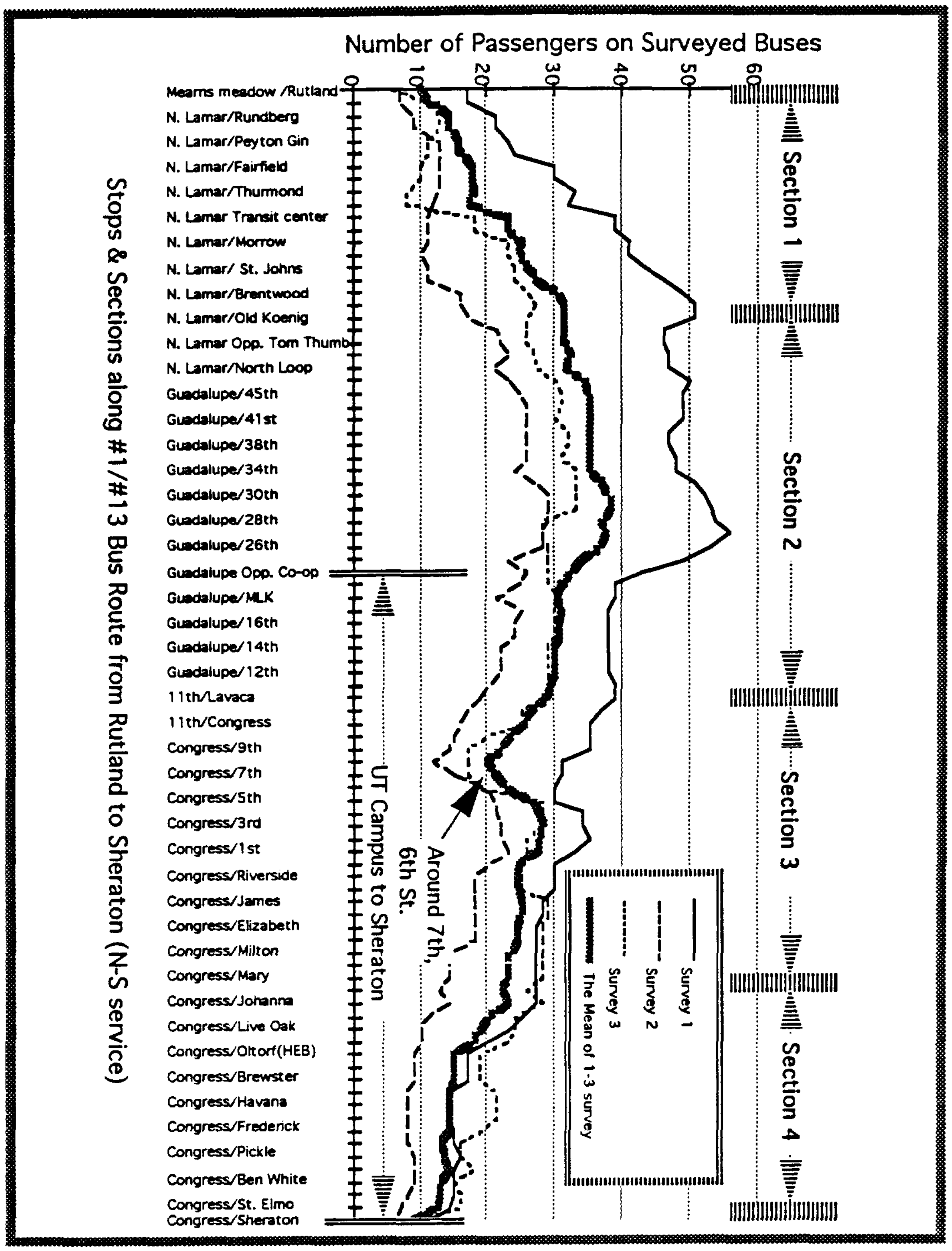


Fig 4.2 Trend of occupancy along #1/#13 Bus Route from north to south

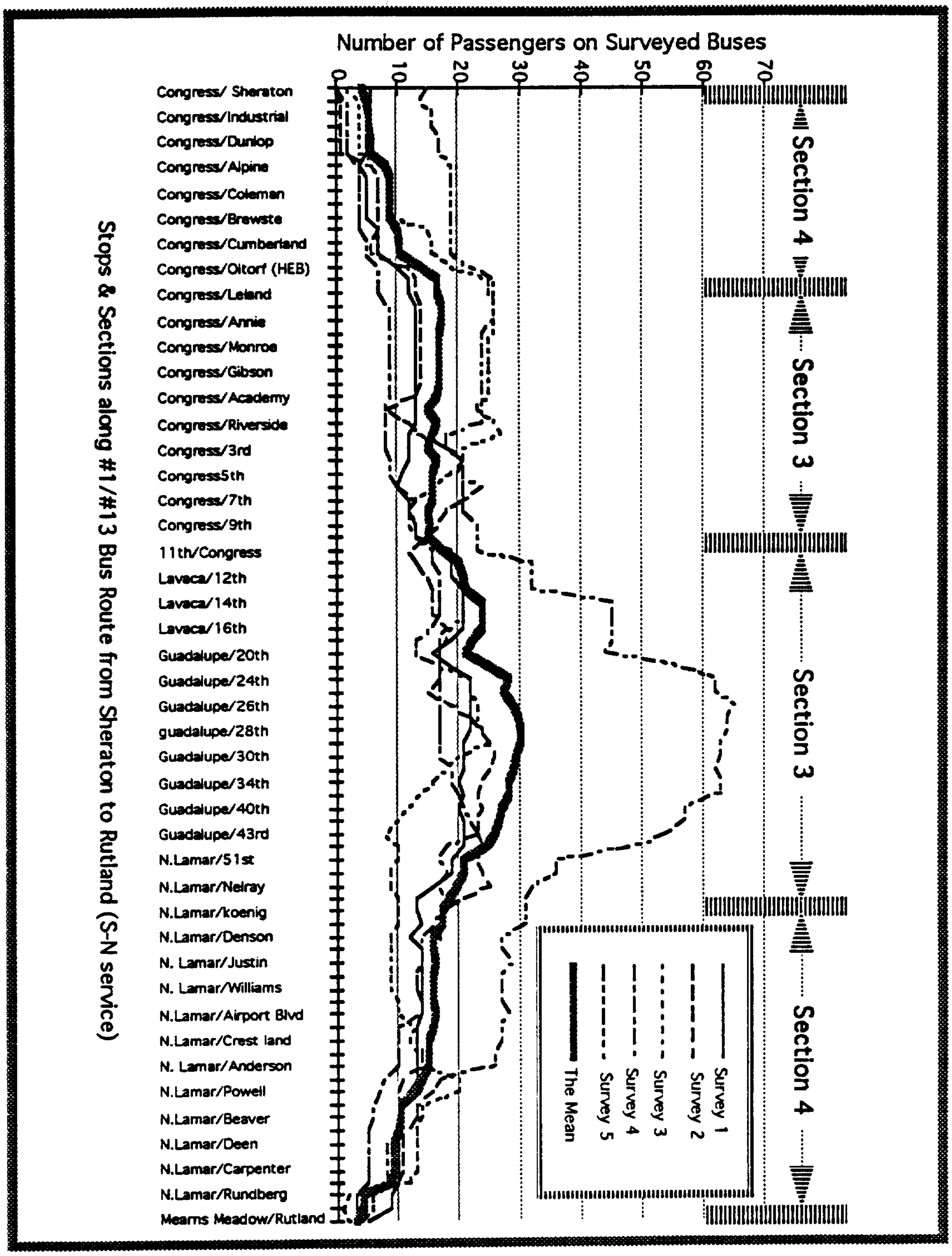


Fig 4.3 Trend of occupancy along #1/#13 Bus Route from south to north

Although passenger occupancy levels surveyed each time are much different, there is a clear occupancy trend which can be condensed to a graphic trend pattern. Figures 4.2 and 4.3 show that indeed some sections always have higher occupancy than the rest of the sections. For #1/#13 bus route, the trend pattern can be generally described by four sections.

1) From the north terminal Rutland to N. Lamar/Koenig Lane is the first section in the trend pattern, as passengers move toward the downtown area and there is more boarding than de-boarding.
2) From Koenig Lane/N. Lamar to 11th Street is the second section. In this section, the bus route passes through a dense student apartment area, UT campus, shopping and dining areas, and the State Capitol. Passenger occupancy in this section is the highest level in the route.

3) The third section is from 11th Street/Congress Avenue to Mary Street. Many passengers de-board for destinations along 8th Street and 6th Street, the most heavily traveled streets in Austin. The level of occupancy is less than it is in the second segment.
4) The fourth section is from Mary Street to the two south bus terminals, at S. Congress/Sheraton Street intersection and at William Cannon/S. Transit Center. This section is located in an area of relatively low population density. Thus, the occupancy goes down and buses often have fewer passengers.

Of course, trend patterns of occupancy are not the same between bus routes. For example, the highest occupancy level on the IF bus route is found at the UT campus, where the bus is crowded with boarding students. Based on the concept of the trend of passenger occupancy along bus routes, each section of a route can be assigned a reasonable passenger load value for calculating ESALs of a bus operated in the section.

TRANSIT PASSENGER OCCUPANCY DATA

Another survey conducted by the study shows that occupancy values differ significantly among weekdays, even though surveys were taken at exactly the same time of each weekday and at exactly the same stop of the route. These observations were carried out on the #1 bus route from UT Co-Op stop to Sheraton St. stop at 12:30 pm for north-to-south service, and at 1:20 pm for south-to-north service each workday. Survey results are shown in Tables 4.1 and 4.2.

TABLE 4.1 PASSENGER OCCUPANCY (NUMBER) ON #1 BUSES AT SAME TIME OF DIFFERENT WEEKDAY (FROM NORTH TO SOUTH)

Bus's ID # :	GILLIG 1121	GILLIG 1105	GILLIG 1105	GILLIG 1105	
Survey Date:	(8/11/93)	(8/12/93)	(8/13/93)	(8/16/93)	
STOPS	Wednesday	Thursday	Friday	Monday	Average
Guadalupe Opp. Co-op	29	27	30	8	24
Guadalupe/21st	30	26	32	10	25
Guadalupe/MLK	30	26	32	15	26
Guadalupe/18th	30	27	30	15	26
Guadalupe/16th	31	28	31	15	26
Guadalupe/15th	31	28	31	15	26
Guadalupe/14th	30	28	31	16	26
Guadalupe/13th	31	28	31	17	27
Guadalupe/12th	31	28	31	17	27
Guadalupe/11th	31	24	30	17	26
11th/Lavaca	27	20	30	17	24
11th/Colorado	23	19	30	17	22
11th/Congress	23	19	22	17	20
Congress/10th	23	18	23	17	20
Congress/9th	21	18	23	17	20
Congress/8th	24	19	27	17	22
Congress/7th	23	15	26	19	21
Congress/6th	21	13	16	17	17
Congress/5th	22	19	18	20	20
Congress/4th	23	19	17	20	20
Congress/3rd	23	20	17	20	20
Congress/2nd	23	20	15	20	20
Congress/1st	27	21	22	24	24
Congress/Barton Springs	27	20	16	24	22
Congress/Riverside	32	20	16	24	23
Congress/Nellie	32	20	16	24	23
Congress/James	31	17	15	23	22
Congress/Gibson	31	17	15	23	22
Congress/Elizabeth	29	17	14	24	21
Congress/Monroe	30	17	14	23	21
Congress/Milton	30	17	14	23	21
Congress/Annie	30	17	14	23	21
Congress/Mary	31	17	15	22	21
Congress/Johanna	30	17	15	22	21
Congress/Crockett	29	16	15	20	20
Congress/Live Oak	23	14	14	18	17
Congress/College	15	11	12	16	14
Congress/Oltorf(HEB)	13	8	13	11	11
Congress/Cumberland	13	8	13	11	11
Congress/Brewster	13	8	13	11	11
Congress/La Vista	9	9	12	10	10
Congress/Havana	9	9	12	10	10
Congress/Coleman	9	9	12	10	10
Congress/Frederick	9	9	13	8	10
Congress/Woodward	9	9	13	8	10

TABLE 4.1 PASSENGER OCCUPANCY (NUMBER) ON #1 BUSES AT SAME TIME OF DIFFERENT WEEKDAY (FROM NORTH TO SOUTH) *(Continued)*

Bus's ID # :	GILLIG 1121	GILLIG 1105	GILLIG 1105	GILLIG 1105	
Survey Date:	(8/11/93)	(8/12/93)	(8/13/93)	(8/16/93)	
STOPS	Wednesday	Thursday	Friday	Monday	Average
Congress/Pickle	7	6	9	8	8
Congress/Post Road	7	5	8	6	7
Congress/Ben White	7	5	8	6	7
Congress/Industrial	7	5	8	3	6
Congress/St. Elmo	6	4	6	3	5
Congress/Sheraton	2	0	2	3	2
Sheraton/Old Castle	2	0	2	3	2
Old Castle/Westmorland	2	1	2	3	2
Fort Clarke/Battle Bend	3	1	2	2	2
Battle Bend/Suburban	3	1	2	2	2
Suburban/Tilbury	3	1	2	2	2
Suburban/Sheraton	3	1	3	2	2
Sheraton/Congress	3	1	3	2	2

TABLE 4.2 PASSENGER OCCUPANCY (NUMBER) ON #1 BUSES AT SAME TIME OF DIFFERENT WEEKDAY (FROM SOUTH TO NORTH)

Bus's ID # :	GILLIG112 1	GILLIG 1121	GILLIG 1105	GILLIG 1105	GILLIG 1105	
Survey Date:	(8/10/93)	(8/11/93)	(8/12/93)	(8/13/93)	(8/16/93)	
	Tuesday	Wednesday	Tuesday	Friday	Monday	Average
Congress/ Sheraton	1	2	2	4	1	2
Congress/St Elmo	2	3	2	5	3	3
Congress/Industrial	3	4	5	8	5	5
Congress/Ben White	3	4	5	8	5	5
Congress/Dunlop	3	5	5	8	5	5
Congress/Post Road	3	5	5	8	5	5
Congress/Alpine	3	5	5	7	5	5
Congress/Woodward	5	5	5	9	6	6
Congress/Coleman	5	5	5	9	7	6
Congress/LaVista	5	5	9	10	8	7
Congress/Brewste	5	6	9	10	9	8
Congress/St. Edwards	5	6	9	10	9	8
Congress/Cumberland	5	6	9	10	9	8
Congress/Long Bow	5	6	9	10	9	8
Congress/Oltorf (HEB)	10	9	11	14	12	11
Congress/Live oak	18	13	16	15	16	16
Congress/Leland	18	13	16	15	16	16
Congress/Mary	19	13	17	15	16	16
Congress/Annie	19	13	17	15	16	16
Congress/Milton	19	13	17	15	16	16
Congress/Monroe	19	13	17	15	18	16
Congress/Elizabeth	19	13	17	15	18	16
Congress/Gibson	19	13	17	15	18	16
Congress/Park	19	13	17	15	18	16

TABLE 4.2 PASSENGER OCCUPANCY (NUMBER) ON #1 BUSES AT SAME TIME OF DIFFERENT WEEKDAY (FROM SOUTH TO NORTH) *(Continued)*

Bus's ID #:	GILLIG112 1	GILLIG 1121	GILLIG 1105	GILLIG 1105	GILLIG 1105	
Survey Date:	(8/10/93)	(8/11/93)	(8/12/93)	(8/13/93)	(8/16/93)	
	Tuesday	Wednesday	Tuesday	Friday	Monday	Average
Congress/Academy	19	15	16	17	20	17
Congress /Congress Square	17	13	15	15	21	16
Congress/Riverside	19	19	15	15	15	17
Congress/2nd	23	16	14	14	12	16
Congress/3rd	23	16	13	14	12	16
Congress/4th	23	16	13	13	13	16
Congress5th	21	19	16	13	11	16
Congress/6th	22	16	23	14	9	17
Congress/7th	24	17	26	15	9	18
Congress/8th	23	20	26	15	10	19
Congress/9th	24	20	28	15	13	20
Congress/10th	24	19	28	14	13	20
11th/Congress	21	27	27	16	13	21
11th/Lavaca	20	27	27	15	14	21
Lavaca/12th	20	27	27	15	14	21
Lavaca/13th	20	27	27	15	14	21
Lavaca/14th	20	27	27	15	14	21
Lavaca/15th	20	27	27	16	14	21
Lavaca/16th	19	27	27	15	14	20
Lavaca/18th	19	24	23	14	14	19
Guadalupe/20th	17	23	22	13	12	17
Guadalupe opp. Co-Op	23	23	25	17	16	21

Data show that for most of the stops, occupancies vary greatly at the same time of day Monday through Friday. A statistical analysis of variance (ANOVA) was used to examine the significance of variance on weekdays. The null-hypothesis (H_0) is that "occupancies at the same time schedule among weekdays are the same." The following is a summary of a one-way ANOVA for data in Table 4.1 (route from north to south). A total of 204 observations in 4 groups (for Wednesday, Thursday, Friday, and Monday) were tested under the null-hypothesis. Results show that the H_0 should be rejected and passenger occupancies are significantly different among the four weekdays at confidence level of a = 0.001.

Source	SS	df	MS	F	P
Sum of square between group	1230.22	3	410.07	6.66	<0.001
Sum of square of error	12321.14	200	61.61		
Total	13551.35	203			

Also, an ANOVA summary for data in Table 4.2 (route from south to north) is shown as follows. A total of 230 values in five groups (for Tuesday, Wednesday, Thursday, Friday, and Monday) were tested under the null-hypothesis. Results show that the passenger occupancy was also significantly different between weekdays at confidence level of a = 0.025 (< 0.05).

Source	SS	df	MS	F	P
Sum of square between group	516.32	4	129.08	2.83	<0.025
Sum of square of error	10263.52	225	45.62		
Total	10779.84	229			

The above analysis indicates that the value of passenger occupancy changes all the time and can only be estimated. Since time, labor and money are usually limited for data collection, an average value may be estimated based on limited survey and used for ESAL calculation.

From 1991 to 1992, Capital Metro carried out surveys on passenger occupancy of all Metro buses and UT shuttle buses. Occupancies of all buses in each route during an operating day were recorded, which amounts to over 10,000 entries. Part of these data were provided by the planning division of Capital Metro and statistically analyzed in this study for calculation of bus ESAL factors.

PASSENGER LOADING DISTRIBUTION

Since passenger loading is a moving load, its center of gravity may be found at any point between the front axle and rear axle of the bus. Generally, the seating area on a bus can be divided into three sections: the front section, the middle section, and the rear section. For example, in a GILLIG 1100 bus (Figure 4.4), the front section includes two rows of longitudinal seats and two transverse seats designed for handicapped passengers and senior citizens since they are close to the front door and driver. The middle section is the main seating area where all seats are transversely arranged. This section has a better view, more privacy, and a more comfortable seating position since human bodies are more sensitive to lateral forces than to back and forward forces. The rear section has mixed seats. Since it is close to the engine and has fewer windows, it is relatively noisy and more isolated. Although the middle section is desirable for passengers, observations often found that passengers prefer empty seats at the back area rather than concentrating in the middle section. So the basic passenger tendency is to spread uniformly over all three seating sections. The reason behind this phenomenon may be that people instinctively try to maintain a sense of personal space around them to make them feel safe and comfortable. Of course, with increasing numbers of passengers, all of the seats are filled, and the corridor is filled with standees.

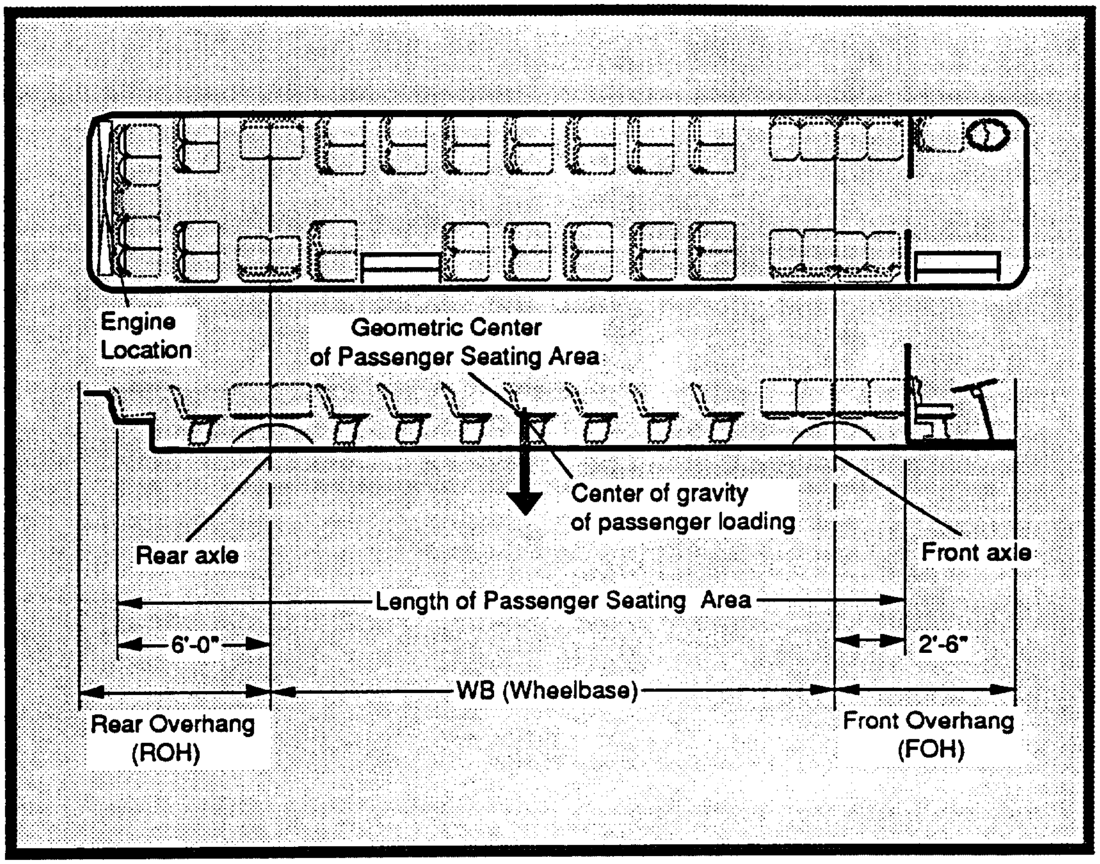


Fig 4.4 Center of Gravity of Passenger Loading (An example of GILLIG Buses)

Based on this phenomenon we can assume that the center of gravity of passenger loading is approximately at the geometric center of the seating area. Generally, for standard bus models the front overhang (FOH) and the rear overhang (ROH) are fixed dimensions, but the wheelbase (WB) varies to meet different overall length (OL) requirements of the bus for seating capacity. As an example, Figure 4.4 shows a layout of the seating area of GILLIG buses. The distance from the front axle to the edge of the seating area and the distance from the rear axle to the edge of the seating area are fixed for all GILLIGs and measured as 2.5' and 6.0', respectively.

Using this model, the length of the passenger seating area is WB + 6' + 2.5' = (WB + 8.5'), and the distance from the geometric center to the front axle is [(WB + 8.5') / 2] - 2.5'. Under the equilibrium between the passenger loading and the two axle reactions, the coefficient of distribution of the passenger loading to front axle and rear axle can be determined. The coefficient for the rear axle is

$$Kr = \{[(WB + 8.5') / 2] - 2.5'\}/WB = 0.5 + (1.75/WB),$$

and for the front axle is

$$Kf = 1 - [0.5 + (1.75/WB)] = 0.5 - (1.75/WB).$$

The average values of above buses are Kr = 0.6 and Kf = 0.4.

The calculated coefficients of distribution of passenger loading to rear and front axle for four GILLIG types are as follows:

BUS SERIES	WB (ft)	Kr	Kf
GILLIG 1700	18.33	0.60	0.40
GILLIG 1600	14.17	0.62	0.38
GILLIG 1100	23.33	0.58	0.42
GILLIG 1000	23.33	0.58	0.42

The distribution coefficient may also be estimated in terms of the difference between gross vehicle weight rated (GVWR) and the bus curb weight. The GVWR is the rated weight of a bus including the weight of maximum passenger loading and fuel. The bus curb weight is calculated as

Curb Weight = GVWR - [(Number of Seats) x 1.5 x 150 lbs],

where,

150 lbs represents the assumed average weight of a passenger.

These two weights are usually specified by bus manufacturers. The difference between these two is solely induced by the passenger load. Using the TMC CNG bus as an example, the two weights are as the following (Refs 23, 24).

Axle	GVWR	Curb Weight
Front axle	14,500 lbs	10,380 lbs
Rear axle	25,000 lbs	18,940 lbs
	Total = 39,500 lbs	29,320 lbs

Then the coefficient of passenger loading distribution may be estimated as

$$Kf = (14500 - 10380) / [(14500 - 10380) + (25000 - 18940)] = 0.4,$$

$$Kr = (25000 - 18940) / [(14500 - 10380) + (25000 - 18940)] = 0.6.$$

For simplification of the analysis, it is assumed that Kf = 0.4 and Kr = 0.6 for all buses when distributing their passenger loading. Although error may occur by using a uniform coefficient, since all traffic loading can only be estimated for pavement engineering, these coefficients are reasonable enough for the purpose of bus loading calculations and pavement design.

SENSITIVITY STUDY OF PASSENGER LOADING

As mentioned before, a standard bus is often referred to as the bus that has two single axles with a total of six wheels and the passenger capacity of more than 50 (including standees). The major contribution to the bus ESALs is made by the rear axle, because the rear axle is much heavier than the front. Generally, the ratio of the rear axle load to the front axle load is about two to one (Ref 25). Most contemporary buses in the U.S. have the engine located at the rear, and the rear overhang (ROH) is much longer than the front overhang (FOH), which contributes to the weight difference. Since curb weights of single rear axles of standard buses are usually close to or in excess of 18,000 lbs, adding a small load to the rear axle could significantly increase bus ESALs.

In order to explore the relationship between passenger occupancy and the ESAL of the bus, a sensitivity study was carried out. This study took the GILLIG 1100 bus as a model. The maximum passenger number on the bus is 1.5 times the seating capacity. The average passenger weight is assumed to be 150 lbs per person as the rule of thumb. Results of the sensitivity study are shown in Table 4.3 and Figure 4.5.

Table 4.3 shows how important passenger occupancy is to bus ESALs. When the bus is full (i.e. 150 percent occupancy), the total ESAL of the bus is a 258 percent net increase over an empty bus. At this point of occupancy, the ESAL of the rear axle is 4.31, which is 93 percent of the total bus ESALs. In other words, under 150 percent passenger occupancy the ESAL of the single rear axle of the bus is as high as 13 times that of the single front axle of the bus. Figure 4.5 shows the results of the sensitivity study, and ESAL in 100 percent represents an empty bus.

TABLE 4.3 DATA FOR SENSITIVITY STUDY ON BUS ESAL VS. PASSENGER OCCUPANCY

Passenger Occupancy %	ESAL of the front axle	ESAL of the rear axle	ESAL of the bus (both axles)	The Relative ESAL of the bus in % value
0%	0.07	1.23	1.295	100%
5%	0.07	1.29	1.359	105%
10%	0.07	1.35	1.425	110%
20%	0.08	1.48	1.565	121%
30%	0.10	1.62	1.717	133%
40%	0.11	1.77	1.880	145%
50%	0.12	1.94	2.055	159%
60%	0.13	2.11	2.243	173%
70%	0.15	2.30	2.444	189%
80%	0.17	2.49	2.660	205%
90%	0.18	2.71	2.891	223%
100%	0.20	2.93	3.137	242%
110%	0.22	3.18	3.401	263%
120%	0.25	3.43	3.681	284%
130%	0.27	3.71	3.980	307%
140%	0.30	4.00	4.298	332%
150%	0.33	4.31	4.636	358%

Note: Passenger occupancy is expressed as percent of the seating capacity. The ESAL is assumed to be 100 percent when the bus is empty of passengers, which can be explained as [(ESAL w/passengers) / (ESAL w/o passengers)] x 100 percent.

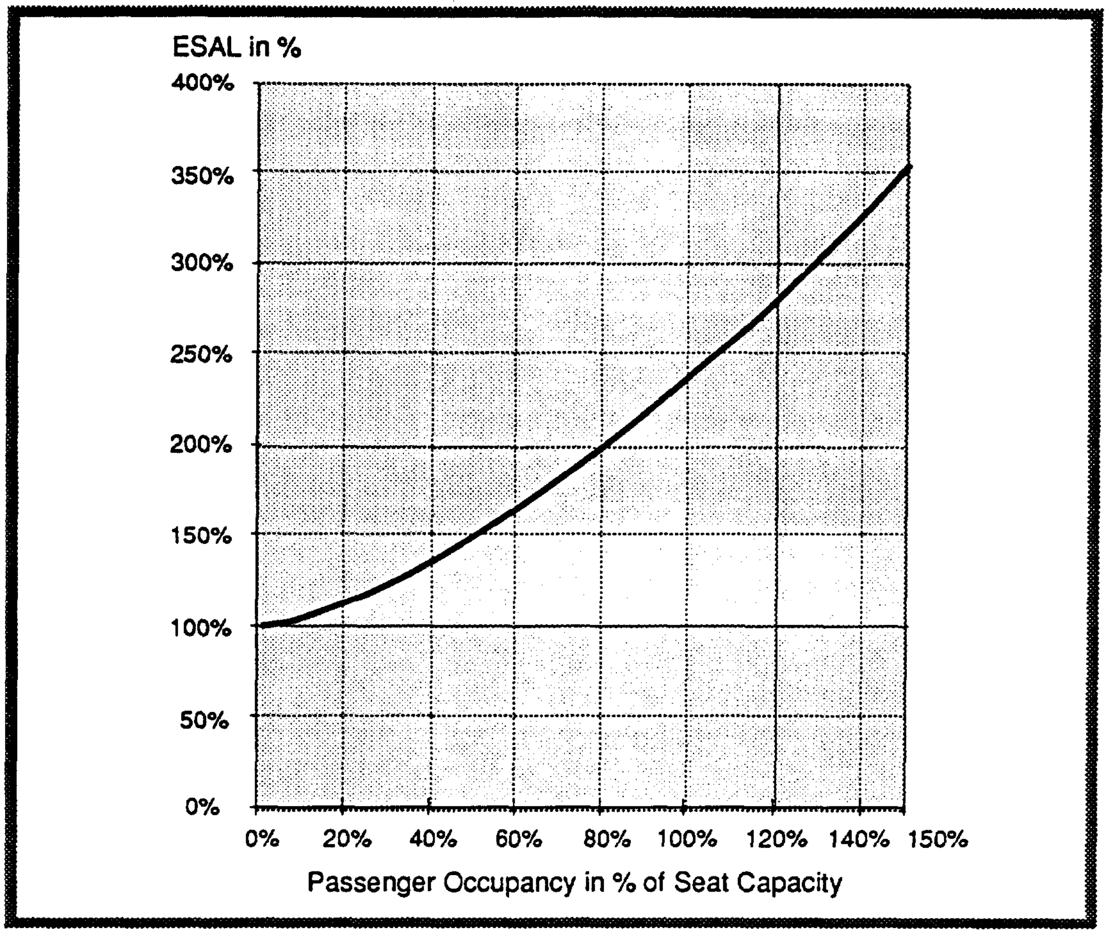


Fig 4.5 Result of sensitivity study: ESAL of bus vs. passenger occupancy

So far, the background of this study has been reviewed, and passenger occupancy has been presented as an important characteristic in determining bus ESALs. The next task of the study is how to determine the bus ESALs. In the following chapter, ESALs of several diesel and CNG buses currently being operated in Austin are determined. Comparison studies between different buses and between buses and passenger cars, pickups, and trucks are also carried out.

CHAPTER 5. CALCULATING LOAD-EQUIVALENCY FACTOR OF BUSES

TRANSIT BUSES IN AUSTIN

Austin is a college town with a population of 482,296 (Ref 26), of which 78,807 are university or college students (Ref 27). Most of them commute to campus on the bus service, so transit buses provide an important public transportation service for the city.

The public transportation system in Austin is called Capital Metro—The Capital Metropolitan Transit Authority —which was established in January 1985 (Ref 28). At the end of 1993, the Capital Metro bus system serviced 63 bus routes covering an area of 471 square miles. It possessed 418 operating vehicles including 123 alternative fueled vehicles (Ref 28), of which about 30 are TMC CNG buses. Capital Metro made a decision in 1992 to build a permanent compressed CNG refueling station to support their growing fleet of CNG-powered buses (Ref 28).

The major diesel buses operated on the fixed routes are GILLIG buses produced by GILLIG Corporation, Hayward, California. A Capital Metro inventory (Ref 29) shows that GILLIG buses accounted for 81 percent of the buses servicing fixed routes. Diesel buses serving fixed routes are shown in Table 5.1.

TABLE 5.1 MAJOR DIESEL BUSES IN CAPITAL METRO FIXED BUS ROUTES

Bus Series	Number of Units	Number of Axles	Length (ft)	Width (in)	Height (in)	Number of Seats
GILLIG 1700	77	2	35	102	127	39
GILLIG 1600	30	2	30	102	127	29
GILLIG 1100	105	2	40	102	127	47
GILLIG 1000	25	2	40	96	127	47
AMG 500	26	2	35	95	125	45
TROLLEY900	22	2	35	101	132	33
TMC 800	7	2	35	98	120	30
Σ=	292 units					

Source: Capital Metro Transit Current Bus Specifications issued by the Austin City Capital Metro on January 20, 1993 (Ref 29).

The GILLIG 1100 and GILLIG 1000 have the same seating capacity, length, and height, but varying width. They account for 130 units of a total 292 diesel buses servicing fixed routes. Figure 5.1 is a sketch of the GILLIG 1100 and 1000 bus. The GILLIG 1100 and 1000 service the University of Texas at Austin shuttle bus system as well as some of the Capital Metro bus service system.

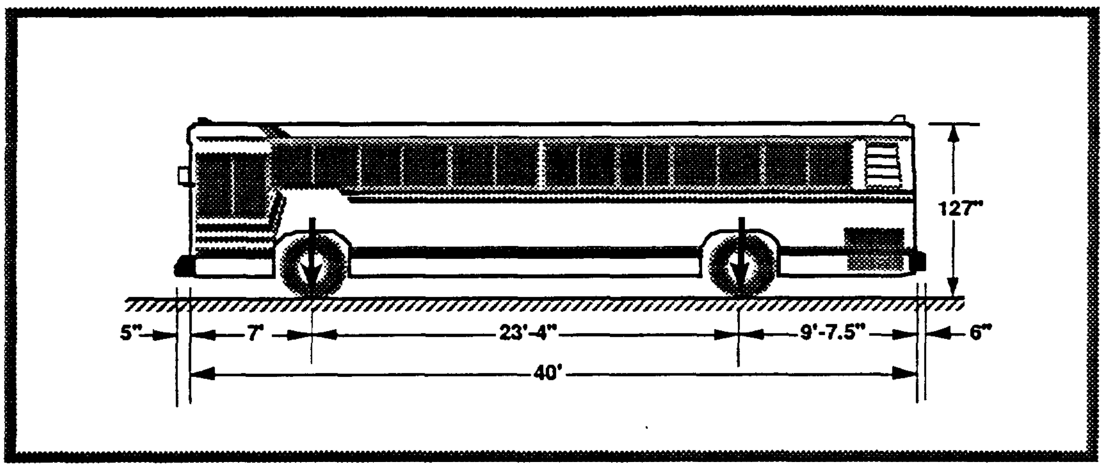


Fig 5.1 Appearance and dimensions of GILLIG 1100 and GILLIG 1000 buses

The CNG fueled standard buses currently operated in Austin are of two types, the TMC CNG bus and the Blue Bird CNG bus. TMC CNG buses currently run on several major Capital Metro bus routes. They have a standard length of 40 ft, width of 102 in, height of 118.5 in, and seating capacity of 43. The Blue Bird CNG bus previously mentioned is operated as a commuter transit bus. It is a prototype bus first tested in Texas, with a length of 37 ft, seating capacity of 40, and is not heavier than its diesel counterpart. However, it may not be comparable with GILLIG buses or appropriate for urban routes since it was not designed for heavy duty metro transit service.

Axle Loads of Buses

As mentioned in Chapter 4, two terms of vehicle weight are commonly used for describing the weight of buses. One is GVWR, the maximum bus weight rated by the bus producer, including the weight of a full passenger load. The other term is bus curb weight, in which the full complement of fuel, oil, and water is counted but passenger loading is not. Curb weight is considered the base weight of buses.

As part of the study conducted by the Center for Transportation Research (CTR) at The University of Texas at Austin and supported by Capital Metro, 10 major bus types, including one TMC CNG bus, were weighed at A-1 Freeman Moving & Storage, Inc., in Austin during July 1993 to determine the curb weight (Ref 30). Buses were weighed according to the following procedure: first, the front axle was weighed with the rear axle off the scale to determine the front axle load; second, both axles were weighed simultaneously; and third, the rear axle was weighed in the same manner as the front axle.

In August and November 1993, the curb weight data of the TMC CNG bus was obtained from the manufacturer (Refs 23, 24). The curb weight of the TMC CNG bus (29,800 lbs) was 101.6 percent of the specified weight (29,320 lbs). The curb weight of the front and rear axles was 11,740 lbs and 18,040 lbs respectively, with the manufacturer weights of the fron and rear axles being 10,380 lbs and 18,940 lbs, respectively. Since the weigh scale and method may not be accurate enough to determine axle weights, the user's data was chosen for the analysis. The rest of the weighed curb weight data was used for analysis since the manufacturer's data was not available. Curb weights of the major buses and their axle loads under various passenger occupancies are shown in Tables 5.2(a) and 5.2(b) along with the Blue Bird CNG bus, which has a curb weight of 25,500 lbs. The front and rear axles of the Blue Bird CNG bus were not weighed separately in this analysis. They were estimated using a weight ratio of front to rear axle of one to two.

TABLE 5.2(a) AXLE LOAD OF THE MAJOR BUSES IN AUSTIN

Types of Buses:		TMC (CNG)		Blue Bird (CNG)		Gillig 1100	
Curb Weight:		29320		25500		28260	
Seating Capacity:		43		40		47	
Type of Axle:		Front	Rear	Front	Rear	Front	Rear
Coefficient of Passenger Load Distribution:		Kf=0.4	Kr=0.6	Kf=0.4	Kr=0.6	Kf=0.4	Kr=0.6
Occupancy: number of passenger	Passenger Loads (kip)	Axle Load of Front and Rear (kip)					
0	0.00	10.38	18.94	8.50	17.00	9.40	18.86
5	0.75	10.68	19.39	8.80	17.45	9.70	19.31
10	1.50	10.98	19.84	9.10	17.90	10.00	19.76
15	2.25	11.28	20.29	9.40	18.35	10.30	20.21
20	3.00	11.58	20.74	9.70	18.80	10.60	20.66
25	3.75	11.88	21.19	10.00	19.25	10.90	21.11
30	4.50	12.18	21.64	10.30	19.70	11.20	21.56
35	5.25	12.48	22.09	10.60	20.15	11.50	22.01
40	6.00	12.78	22.54	10.90	20.60	11.80	22.46
45	6.75	13.08	22.99	11.20	21.05	12.10	22.91
50	7.50	13.38	23.44	11.50	21.50	12.40	23.36
55	8.25	13.68	23.89	11.80	21.95	12.70	23.81
60	9.00	13.98	24.34	12.10	22.40	13.00	24.26
65	9.75	14.28	24.79			13.30	24.71
70	10.50					13.60	25.16

TABLE 5.2(b) AXLE LOAD OF THE MAJOR BUSES IN AUSTIN

Types of Buses:		GILLIG 1700		GILLIG 1600		Trolly 900 (Dillo)	
Curb Weight:		26380		25080		20800	
Seating Capacity:		39		29		33	
Type of Axle:		Front	Rear	Front	Rear	Front	Rear
Coefficient of Passenger Load Distribution:		Kf=0.4	Kr=0.6	Kf=0.4	Kr=0.6	Kf=0.4	Kr=0.6
Occupancy: number of passenger	Passenger Loads (kip)	Axle Load of Front and Rear (kip)					
0	0.00	8.40	17.98	7.32	17.76	10.94	9.88
5	0.75	8.70	18.43	7.62	18.21	11.24	10.33
10	1.50	9.00	18.88	7.92	18.66	11.54	10.78
15	2.25	9.30	19.33	8.22	19.11	11.84	11.23
20	3.00	9.60	19.78	8.52	19.56	12.14	11.68
25	3.75	9.90	20.23	8.82	20.01	12.44	12.13
30	4.50	10.20	20.68	9.12	20.46	12.74	12.58
35	5.25	10.50	21.13	9.42	20.91	13.04	13.03
40	6.00	10.80	21.58	9.72	21.36	13.34	13.48
45	6.75	11.10	22.03	10.02	21.81	13.64	13.93
50	7.50	11.40	22.48	-	-	13.94	14.38
55	8.25	11.70	22.93	-	-	-	-
60	9.00	12.00	23.38	-	-	-	-
65	9.75	-	-	-	-	-	-
70	10.50	-	-	-	-	-	-

Bus curb weight (Refs 23, 24, 30). For coefficients of passenger load distribution Kf and Kr, see Chapter 4.

EQUIVALENT SINGLE AXLE LOAD (ESAL) OF BUSES

Over 90 percent of the buses operated on fixed routes in Austin have single rear axle loads greater than 20,000 lbs, which is the single axle load limit on state and interstate highways in Texas. Within the Austin city limits, however, there is no such single axle load limit for vehicles, according to the City Street and Bridge Division. Therefore, within the city, buses are the heaviest vehicles. City transportation officials estimate that heavy buses are responsible for 70 to 90 percent of damage to the streets on the bus routes (Ref 31). Capital Metro has pledged to give the City of Austin an estimated $60.2 million to help repair "neglected" Austin streets over the next 10 years. In addition, Capital Metro has given the city $4.4 million annually for street repairs and other transit projects since 1989.

ESALs for different pavement structure combinations, axle configurations, and terminal serviceability are calculated by AASHO Road Test-based equations. The following are the equations transformed in a convenient form (Ref 32) for calculating ESALs for flexible pavement.

$$e_i = [(L_i + n)^{4.79} \times (10^{Gi/\beta 18})] / [(18+1)^{4.79} \times (10^{Gi/\beta i}) \times (n^{4.33})]$$

where

e_i = equivalence factor of axle load or the number of ESALs of 18,000 Lbs,

L_i = axle load of the axle-set, kips,

$Gi = \log [(4.2 - Pt) / (4.2 - 1.5)]$,

$\beta i = 0.4 + [0.081 (L_i + n)^{3.23}] / [(SN + 1)^{5.19} n^{3.23}]$

$\beta 18 = 0.4 + [0.081 (18 + 1)^{3.23}] / [(SN + 1)^{5.19}$

n = number of axles,

Pt = the minimum acceptable PSI (present serviceability index) or terminal PSI level, and

SN = the structural number of a flexible pavement.

In order to provide convenient tables of ESALs for further analysis, ESALs of buses under a range of Pt = 2.0 & 2.5 and SN = 2 to 5 of flexible pavements have been computed and listed in Appendix 1. In this study, structure numbers of flexible pavements for different streets in Austin are estimated between SN = 2 and 3, referring to the AASHTO Guide of Design (Ref 33).

COMPARISON STUDY UNDER EQUIVALENCY

Any comparison should be based on equal condition, whether it is between buses or between buses and other vehicles. Since passenger capacities of the buses involved in this study are not the same, these buses may not be directly comparable in terms of their ESAL factors. However, we may use a term called "ESAL per passenger seat" to make an equivalent comparison. If Pt = 2.0 and SN = 2.5, and each bus is fully occupied, then the ESAL comparison of the buses is as follows:

Type	Seating	ESAL of the Bus	ESAL per passenger seat
TMC CNG	43	3.067	0.071
GILLIG 1100	47	3.170	0.067
GILLIG 1700	39	2.280	0.058
GILLIG 1600	29	1.769	0.061

The ESAL per passenger seat of TMC CNG bus is six percent greater than that of the GILLIG 1100 diesel bus, 22 percent greater than that of the GILLIG 1700, and 16 percent greater than that of the GILLIG 1600. The ESAL per passenger seat represents the effect of the bus load on a pavement in terms of seating capacity. It may be used theoretically as an index of bus loading efficiency.

In order to show how buses consume street pavements, buses are compared with passenger cars, pickups and trucks, as shown in Tables 5.3 and 5.4. In this comparison, it is again assumed that Pt = 2.0, SN = 2.5, and light and medium passenger cars weigh 2,000 lbs and 4,000 lbs, respectively. Pickups and five-axle tractor-semitrailers weigh 5,500 lbs and 80,000 lbs, respectively. In summary, it can be seen that buses are the heaviest vehicles operating on city streets. Although passenger cars and pickups may account for up to 90 percent and nine percent of average daily traffic volume (ADT) in streets, respectively, they have little impact on pavement deterioration and, therefore, are often ignored in pavement design (Ref 34).

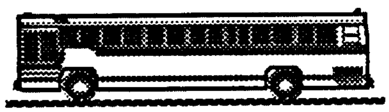
In this chapter, methods for determining bus axle loads and load equivalent factors (ESAL) are described. ESALs of such buses under various conditions are also calculated. Results of these calculations are listed in Appendix 1. These calculations are the basic data preparation for estimation of bus impacts in Chapters 7 and 8, and could be used as references for other purposes.

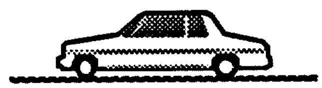
To determine pavement consumption on streets, the heavy traffic on a bus route has to be grouped into buses and trucks (passenger cars and pickups are neglected). This is necessary so that the appropriate level of pavement consumption can be allocated to each group of vehicles and the impact of CNG buses on such pavements can be fairly evaluated. Obviously, besides determination of load equivalencies of buses, truck traffic on bus routes should be reasonably determined. This will be described in the next chapter.

TABLE 5.3 COMPARING BUSES WITH CARS AND PICKUPS UNDER AXLE LOAD EQUIVALENCY

UNDER AXLE LOAD EQUIVALENCY

Flexible Pavement, Pt = 2 , SN = 2.5





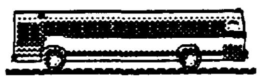
ONE TRANSIT BUS EQUALS NUMBERS OF CARS OR PICKUPS

1 GILLIG 1100 Bus with	Light cars (2000 lbs)	Medium cars (4000 lbs)	Pickups (5500 lbs)
0 Passengers	21530	2950	1030
15 Passengers	29180	3980	1390
25 Passengers	35400	4830	1710
47 Passengers (seating capacity)	52830	7200	2520
70 Passengers (maximum)	77790	10610	3700
1 TMC CNG bus with			
0 Passengers	22470	3070	1070
15 Passengers	30400	4150	1450
25 Passengers	36830	5020	1750
43 Passengers (seating capacity)	51120	6970	2520
65 Passengers (maximum)	74270	10130	3540

TABLE 5.4 COMPARING BUSES WITH TRUCKS UNDER AXLE LOAD EQUIVALENCY

UNDER AXLE LOAD EQUIVALENCY

Flexible Pavement, Pt = 2 , SN = 2.5



ONE TRANSIT BUS EQUALS NUMBERS OF TRUCKS

1 GILLIG 1100 Bus with	Five-Axle Tractor-Semitrailer (3-S2), Total weight: 80000 lbs
0 Passengers	0.55
15 Passengers	0.75
25 Passengers	0.91
47 Passengers (seating capacity)	1.35
70 Passengers (maximum)	2.00
1 TMC CNG bus with	
0 Passengers	0.58
15 Passengers	0.78
25 Passengers	0.94
43 Passengers (seating capacity)	1.31
65 Passengers (maximum)	1.90

CHAPTER 6. TRUCK TRAFFIC ON AUSTIN BUS ROUTES

In this impact study, determination of associated truck traffic on bus routes is important because buses share the right-of-way with truck traffic. In other words, truck traffic has certain significance affecting the evaluation of CNG bus impact. As mentioned in Chapter 5, passenger cars and pickups have little effect on a pavement and, therefore, are neglected in the impact evaluation. Trucks as a heavy vehicle group on bus routes will be studied in greater detail in this chapter.

AUSTIN VEHICLE CLASSIFICATION DATA

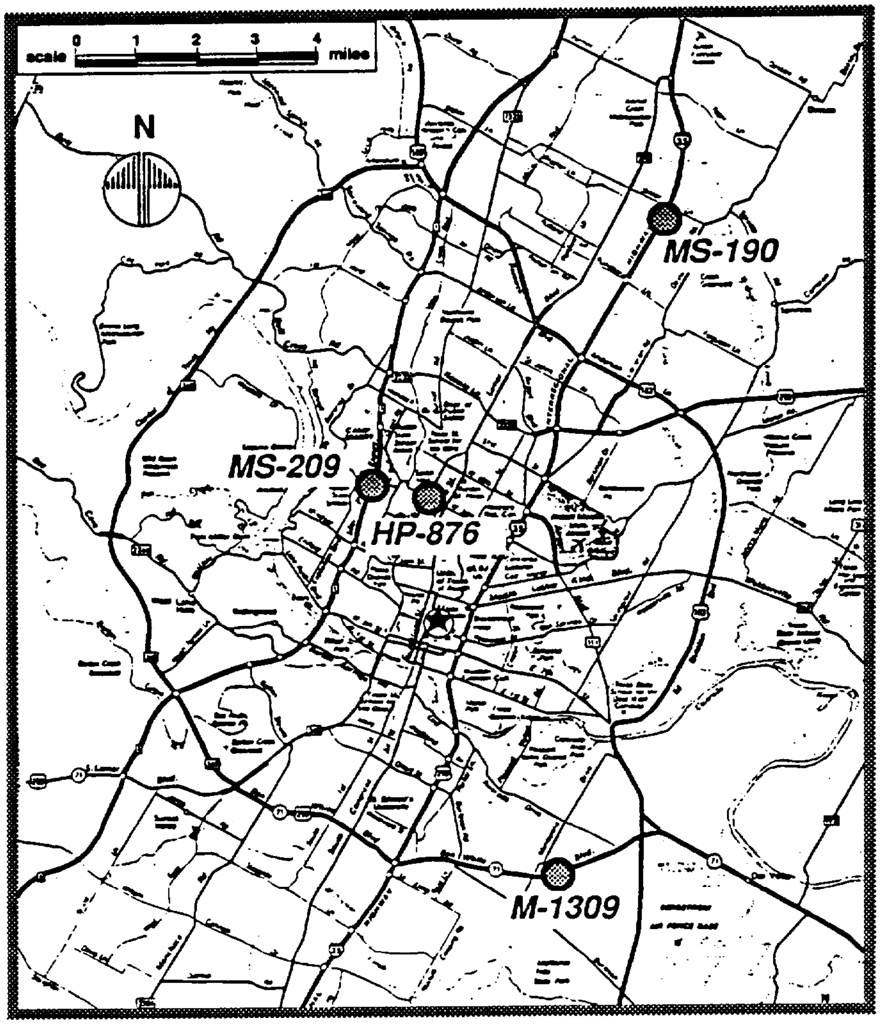
Traffic loading seems one of the most difficult variables to be determined or predicted since it is dynamic and influenced by many factors. Since highway agencies concentrate their data collection on major state or interstate highways, there is little vehicle classification data reported for city streets. For bus routes, bus use can be calculated accurately from the schedules, but the volume of associated traffic—especially truck traffic—on streets can only be estimated by the limited data sources in urban areas.

Two data sources are published periodically by TxDOT. One is the Vehicle Classification Annual Report (Refs 35, 36), in which three or four traffic count stations have records of vehicle classification in Austin. Another source is the Traffic Map of Travis County, Texas, published every four years (Ref 37), which provides traffic ADT data for the City of Austin.

The Vehicle Classification Report, together with the manual count station map, are prepared by the Transportation Planning Division of the Texas Department of Transportation. Vehicle classification data in these reports were collected by manual count stations located all over the Texas highway system. There are about 400 count stations in rural areas and about 80 count stations in urban areas. Not all stations are being activated for collecting data each year.

Vehicle classification data are collected manually. Before 1988, traffic was counted by a device called an Automatic Traffic Recorder. This recorder was able to count the number of vehicles but unable to recognize the type of vehicles. The recorded number of units were eventually modified manually by using ADT factors to get the classified vehicle data. Since 1988, the vehicle classification data has been counted and observed by field workers. Recorded data at each station for each year are based on a single weekday 24-hour observation period. The day on which the observation takes place is randomly chosen between Monday and Friday of any weekday of the reported year.

Figure 6.1 shows four count stations which are located on IH-35 (MS-190), SH-71 (M-1309), Loop-1 (MOPAC) (MS-209), and N. Lamar-38th St. (HP-876). Stations MS-209 and HP-876 are close to the center of Austin, and therefore the data generated from these two stations are more useful to this study. Data from these sources are selected and summarized in Tables 6.1, 6.2, 6.3, and 6.4. Vehicle classification counts and percentage distributions of trucks, pickups, and buses at each station are listed in these tables.



Source: Ref 22

Fig 6.1 Location of count stations in Austin

TABLE 6.1 24-HOUR AVERAGE VEHICLE CLASSIFICATION AT THE STATION MS-190
STATION LOCATION: IH-35, NORTH OF AUSTIN

Report Year:	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Classified vehicle											
Passenger Cars	25389		33729	39524	43052	43336	49505		43977	60425	66832
Panel and Pickup Trucks:	10105		16998	19267	20725	19996	25942		21285	9750	11767
Single Unit: 2-axle	1287		1814	2342	2095	2197	1654		1469	1518	1703
Single Unit: 3-axle	377		621	1655	1190	1048	519		282	390	459
Single Unit: 4-axle	0		0	0	0	0	0		6	3	14
Semi-Trailer: 3-axle	148		158	124	113	96	117		293	134	218
Semi-Trailer: 4-axle	424		403	439	398	364	315		577	230	355
Semi-Trailer: 5-axle	3650		3632	4743	4406	4036	3604		3484	4404	4394
Semi-Trailer: 6-axle or more	52		25	75	80	82	41		29	33	46
Semi-Trailer-Trailer: 5-axle	113		93	109	161	166	169		195	270	320
Semi-Trailer-Trailer: 6-axle	21		89	75	80	64	55		46	341	86
Semi-Trailer-Trailer: 7-axle	0		0	0	0	0	0		0	0	1
Truck & Trailer: 3-axle	24		33	46	38	27	6		0	0	0
Truck & Trailer: 4-axle	96		109	184	132	221	211		0	0	0
Truck & Trailer: 5-axle	54		55	53	44	42	36		0	0	0
Truck & Trailer: 6-axle or more	6		10	10	5	12	2		0	0	0
Total Trucks (Pickup excluded)	6252		7042	9855	8742	8355	6729		6381	7323	7596
Buses: 2-axle and 3-axle	122		140	140	161	201	135		113	113	161
Total Vehicles	41868		57909	68786	72680	71888	82311		71756	77611	86356
Buses as % of total vehicles	0.29%		0.24%	0.20%	0.22%	0.28%	0.16%		0.16%	0.15%	0.19%
Trucks as % of total vehicles	15%		12%	14%	12%	12%	8%		9%	9%	9%
Pickup as % of total vehicles	24%		29%	28%	29%	28%	32%		30%	13%	14%

Source: Refs 35, 36

TABLE 6.2 24-HOUR AVERAGE VEHICLE CLASSIFICATION AT THE STATION M-1309 STATION LOCATION: SH-71, SOUTHEAST OF AUSTIN

The Report Year:	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Number of classified vehicles											
Passenger Cars	12982	-	-	-	18644	-	15474	15740	11971	19086	20863
Panel and Pickup Trucks	5454	-	-	-	8980	-	9387	8631	7446	3659	4774
Single Unit: 2-axle	870	-	-	-	1172	-	779	819	653	292	847
Single Unit: 3-axle	505	-	-	-	1446	-	661	449	457	134	168
Single Unit: 4-axle	0	-	-	-	0	-	0	0	1	1	2
Semi-Trailer: 3-axle	62	-	-	-	70	-	66	45	143	57	83
Semi-Trailer: 4-axle	90	-	-	-	132	-	63	100	117	69	32
Semi-Trailer: 5-axle	549	-	-	-	1102	-	776	566	606	561	478
Semi-Trailer: 6-axle	31	-	-	-	33	-	20	16	9	6	12
Semi-Trailer-Trailer: 5-axle	0	-	-	-	0	-	4	4	5	9	5
Semi-Trailer-Trailer: 6-axle	0	-	-	-	0	-	2	0	1	0	1
Semi-Trailer-Trailer: 7-axle	0	-	-	-	0	-	0	0	0	0	0
Truck & Trailer: 3-axle	18	-	-	-	11	-	5	0	0	0	0
Truck & Trailer: 4-axle	41	-	-	-	70	-	52	101	0	0	0
Truck & Trailer: 5-axle	50	-	-	-	27	-	24	17	0	0	0
Truck & Trailer: 6-axle or more	7	-	-	-	9	-	3	12	0	0	0
Total trucks (Pickup excluded)	2223				4072		2455	2129	1992	1129	1628
Buses: 2-axle and 3-axle	132	-	-	-	179	-	15	106	79	41	109
Total Vehicles	20791				31875		27331	26606	21488	23915	27374
Buses as % of total vehicles	0.63%				0.56%		0.05%	0.40%	0.37%	0.17%	0.40%
Trucks as % of total vehicles	11%				13%		9%	8%	9%	5%	6%
Pickup as % of total vehicles	26%				28%		34%	32%	35%	15%	17%

Source: Refs 35, 36

TABLE 6.3 24-HOUR AVERAGE VEHICLE CLASSIFICATION AT THE STATION MS-209 THE STATION IS LOCATED ON LOOP-1, NORTHWEST OF AUSTIN

The Report Year:	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Number of classified vehicles											
Passenger cars						75499	69826		87588	76482	93663
Panel and Pickup Trucks						23585	27631		26653	8563	9847
Single Unit: 2-axle						1510	1056		923	898	800
Single Unit: 3-axle						297	277		234	152	78
Single Unit: 4-axle						0	0		2	0	7
Semi-Trailer: 3-axle						69	34		273	49	62
Semi-Trailer: 4-axle						64	28		174	26	40
Semi-Trailer: 5-axle						121	132		111	66	88
Semi-Trailer: 6-axle or more						13	7		4	2	3
Semi-Trailer-Trailer: 5-axle						5	0		0	0	1
Semi-Trailer-Trailer: 6-axle						0	0		0	0	0
Semi-Trailer-Trailer: 7-axle						0	0		0	0	0
Truck & Trailer: 3-axle						33	0		0	0	0
Truck & Trailer: 4-axle						96	23		0	0	0
Truck & Trailer: 5-axle						10	0		0	0	0
Truck & Trailer: 6-axle or more						1	0		0	0	0
Total Trucks (Pickup excluded)						2219	1557		1721	1193	1079
Buses: 2-axle and 3-axle						417	86		466	258	336
Total Vehicles						101720	99100		116428	86496	104925
Buses as % of the total vehicles						0.41%	0.09%		0.40%	0.30%	0.32%
Trucks as % of total vehicles						2%	2%		1%	1%	1%
Pickups as % of total vehicles						23%	28%		23%	10%	9%

Source: Refs 35, 36

TABLE 6.4 24-HOUR AVERAGE VEHICLE CLASSIFICATION AT THE STATION HP-876 LOCATION ON N. LAMAR AND SOUTH OF 38TH STREET

The Report Year:	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Number of classified vehicles	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Passenger Cars											27426
Panel and Pickup Trucks											2761
Single Unit: 2-axle											225
Single Unit: 3-axle											12
Single Unit: 4-axle											0
Semi-Trailer: 3-axle											13
Semi-Trailer: 4-axle											9
Semi-Trailer: 5-axle											12
Semi-Trailer: 6-axle or more											0
Semi-Trailer-Trailer: 5-axle											2
Semi-Trailer-Trailer: 6-axle											0
Semi-Trailer-Trailer: 7-axle											0
Truck & Trailer: 3-axle											0
Truck & Trailer: 4-axle											0
Truck & Trailer: 5-axle											0
Truck & Trailer: 6-axle or more											0
Total Trucks (Pickup excluded)											273
Buses: 2-axle and 3-axle											7
Total Vehicles											30467
Buses in % of total vehicles											0.02%
Trucks in % of total vehicles											1%
Pickups in % of total vehicles											9%

Source: Ref 35, 36

DETERMINATION OF TRUCKS ON BUS ROUTES

The percentage distributions of trucks (not pickups) from 1988 to 1992 at each station are the following:

1)	MS-190 station on IH-35	Trucks: eight to nine percent
2)	M-1309 station on SH71	Trucks: nine to six percent (decreasing)
3)	MS-209 station on Loop 1	Trucks: one percent
4)	HP-876 station on N. Lamar	Trucks: one percent (1992 only)

Since stations MS-209 and HP-876 are close to the center of Austin, the truck percentages at these two stations are valuable references for determining the truck percentage in associated traffic on bus routes. Based on the data from these two stations, it is assumed that on Austin streets, the maximum percentage of trucks in associated traffic of the bus route is not greater than one percent.

The percentage of trucks will vary from city to city and this should be incorporated in pavement design. The Asphalt Institute (Ref 38) recommended that the percentage of heavy trucks on city streets be five percent of traffic or less under average conditions in the U.S. Transportation engineers in Colorado have studied vehicle classifications on urban streets (Ref 39), suggesting that in Colorado, the percentages of single unit trucks and tractor-trailer combinations of an average weekday vehicle classification in urban street traffic were as follows (pickups and buses were not included):

1)	for major and arterial streets	(6.9+0.34) = 7.24 percent,
2)	for major collector streets	(6.71+0.07) = 6.78 percent,
3)	for minor collector streets	(5.51+0.03) = 5.54 percent, and
4)	for commercial/multifamily locals	(6.0+0.27) = 6.27 percent.

In these references the percentages of trucks in ADT of streets are greater than five percent. However, vehicle classification data from Austin show that only on IH 35 and SH 71 are the percentage of trucks greater than five (from five to nine percent).

Vehicle registration statistics in Travis County (Austin area) listed in Table 6.5 show further evidence that the percentage of trucks weighted over 6,000 lbs was between 3.4 and 2.9 percent from 1988 to 1992.

TABLE 6.5 TRUCK (OVER 6,000 LBS) REGISTRATION IN TRAVIS COUNTY (AUSTIN AREA)

Year of Registration	Total Number of Vehicles	Number of Trucks (6.0 k lbs to 8.5 k lbs)	Number of Trucks (> 8.5 k lbs)	Total Number of Trucks (weight >6 k lbs)	Percent truck (weight >6 k)
1988	427427	8155	6522	14677	3.4%
1989	404672	7403	5688	13091	3.2%
1990	422867	7626	5360	12986	3.1%
1991	435057	7536	5112	12648	2.9%
1992	445470	7726	5111	12837	2.9%

Source: Ref 40

Austin has no heavy industry or transportation port requiring major truck transportation. Commercial and industrial centers in Texas, such as Houston, Dallas, and San Antonio, have relatively higher truck percentages, as seen in Table 6.6.

TABLE 6.6 TRUCK (OVER 6,000 LBS) REGISTRATION IN HARRIS COUNTY (HOUSTON), DALLAS COUNTY (DALLAS), AND BEXAR COUNTY (SAN ANTONIO)

1) Harris County (Houston)

Year of Registration	Total Number of Vehicles	Number of Trucks (6.0 k to 8.5 k)	Number of Trucks (> 8.5 k)	Total Number of Trucks (weight >6 k lb)	Percent truck (weight >6 k)
1988	1982934	41253	37484	78737	4.0%
1989	1897694	39452	35644	75096	4.0%
1990	2024208	42195	38687	80882	4.0%
1991	2194659	45352	41653	87005	4.0%
1992	2191323	46031	41137	87168	4.0%
1993	2115083	45960	39882	85842	4.1%

2) Dallas County (Dallas)

Year of Registration	Total Number of Vehicles	Number of Trucks (6.0 k to 8.5 k)	Number of Trucks (> 8.5 k)	Total Number of Trucks (weight >6 k lb)	Percent truck (weight >6 k)
1988	1478765	28104	31152	59256	4.0%
1989	1389036	26478	28521	54999	4.0%
1990	1452623	27418	28951	56369	3.9%
1991	1515185	27310	29412	56722	3.7%
1992	1482490	26319	28360	54679	3.7%
1993	1422596	25890	26840	52730	3.7%

3) *Bexar County (San Antonio)*

Year of Registration	Total Number of Vehicles	Number of Trucks (6.0 k to 8.5 k)	Number of Trucks (> 8.5 k)	Total Number of Trucks (weight >6 k lb)	Percent truck (weight >6 k)
1988	825685	18119	17117	35236	4.3%
1989	785876	17097	15609	32706	4.2%
1990	818645	17710	15206	32916	4.0%
1991	870020	18489	15289	33778	3.9%
1992	881131	18900	15434	34334	3.9%
1993	862176	18666	15325	33991	3.9%

Source: Ref 41

Since trucks are more likely to operate on freeways than city streets, the percentage of trucks on city streets should be lower than the percentage of trucks actually registered. Based on vehicle classification data and the above reasoning, this study assumes the following truck percentages for different street categories in Austin:

1) 1.0 percent trucks in ADT on Arterial streets,
2) 0.8 percent trucks in ADT on Collector streets, and
3) 0.6 percent trucks in ADT on Residential streets.

AVERAGE DAILY TRAFFIC (ADT) VOLUME

As previously mentioned, another source of data is the 1992 Traffic Map of Travis County, Texas (Ref 37), containing 24 maps prepared by the Division of Transportation Planning of TxDOT and published every four years. These maps show 24-hour axle counts divided by two during the period July 15, 1992 through November 23, 1992 on the major streets of the Austin urban area. Data were obtained from a device called an air-driven switch count recorder or accumulative-count recorder (ACR), which counts the number of axles when vehicles pass over the recorder. These data were recorded on a weekday randomly chosen from Monday to Thursday. Each number shown on the traffic map is the 24-hour total number of axles counted divided by two, assuming that each vehicle has two axles.

In order to confirm that vehicles generally have two axles, or that the so-called "axle factor" is equal to two in Austin, the ratio of the number of axles to the number of vehicle units of various types of vehicles from the classification reports of the four stations is shown in Table 6.7. The overall mean of the ratios or the axle factor from Table 6.7 is 2.13, which can be rounded to two. This confirms that the 1992 Traffic Map of Travis County, Texas can directly be used as ADT for the bus route system in the City of Austin.

TABLE 6.7 THE RATIO OF THE NUMBER OF TOTAL AXLES TO THE NUMBER OF RELATED TOTAL VEHICLE UNITS

Station/Year		1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
MS-190	Total Vehicles	41868		57909	68786	72680	71888	82311		71756	77611	86356
	Total Axles	97092		129490	155998	162254	159481	178135		156590	171730	188802
	Axle/Unit Ratio	2.32		2.24	2.27	2.23	2.22	2.16		2.18	2.21	2.19
M-1309	Total Vehicles	20791				31875		27331	26606	21488	23915	27374
	Total Axles	44378				69236		58136	55981	45685	49895	56568
	Axle/Unit Ration	2.13				2.17		2.13	2.11	2.13	2.09	2.07
MS-209	Total Vehicles						101720	99100		116428	86496	104925
	Total Axles	-					204623	199037		234064	173451	210363
	Axle/Unit Ratio						2.01	2.01		2.01	2.01	2.01
HP-876	Total Vehicles											30467
	Total Axles											61019
	Axle/Unit Ratio											2.00

Source: Refs 35, 36

TRAFFIC GROWTH RATE

Traffic growth rate is a required input parameter in pavement design and cost analysis. Since almost all the ESALs applied on pavements on bus routes are attributed to heavy trucks and buses, consideration of traffic growth rate should essentially be based on these two vehicle categories. Table 6.8 shows the growth rate of trucks (weighted over 6,000 lbs) registered in Travis County (Austin area) from 1988 to 1992.

TABLE 6.8 THE GROWTH RATE OF TRUCKS (OVER 6,000 LBS) REGISTERED IN TRAVIS COUNTY, TEXAS

Year	6.0 K TO 8.5 K	> 8.5 K	TOTAL	Truck Growth Rate
1988	8155	6522	14677	
1989	7403	5688	13091	-10.81%
1990	7626	5360	12986	-0.80%
1991	7536	5112	12648	-2.60%
1992	7726	5111	12837	1.49%

Source: Ref 40

The report also uses population growth rate to estimate traffic growth. Table 6.9 shows the correlation between human population and vehicle population in Texas during the period of 1988 to 1992. These data were based on a study originally conducted by the Division of Motor Vehicle Titles and Registration, TxDOT. It shows a high correlation between human population and vehicle population. In this analysis, the coefficient of determination or the R-square (R^2) is equal to 0.92, which is high and indicates that 92 percent of the vehicle variance can be predicted by the variance of people population. The mean vehicle growth rate during this period is 1.46 percent.

TABLE 6.9 THE CORRELATION BETWEEN PEOPLE POPULATION AND VEHICLE POPULATION IN STATE OF TEXAS (1980 TO 1992)

Year	People Population	Total Vehicles	Ratio of Vehicle to People	Vehicle Growth Rate
1980	14338100	11756833	82.00%	
1981	14766000	12419606	84.11%	5.64%
1982	15376000	12719194	82.72%	2.41%
1983	15818000	13059415	82.56%	2.67%
1984	16082700	13508355	83.99%	3.44%
1985	16389000	13729625	83.77%	1.64%
1986	16685000	13643820	81.77%	-0.62%
1987	16781494	13492500	80.40%	-1.11%
1988	16834000	13550000	80.49%	0.43%
1989	16991002	13740000	80.87%	1.40%
1990	16986510	13908880	81.88%	1.23%
1991	17386691	13934462	80.14%	0.18%
1992	17615745	13963403	79.27%	0.21%
1. MEAN	16311557.08	13340468.69	81.84%	1.46%
2. STD DEV	994476.0342	669771.2765		
3. CORRELATION COEFFICIENT OF POPULATION AND VEHICLE:		0.958		
4. COEFFICIENT OF DETERMINATION:		0.919		

Source: Mr. Martin "Jake" Jakubowsky of the Division of Motor Vehicle Titles and Registration, TxDOT.

In addition, a population projection for Travis County (Austin area) from 1990 to 2003 (Ref 42) is shown in Table 6.10. The average projected population growth rate in Austin during this period is 0.93 percent. Based on the high correlation between people and vehicles and the given growth rate of people population, we can assume that vehicle growth rate in Austin will be around one percent. Bus growth rate should depend on the city population growth rate, and Capital Metro believes passenger growth rate is likely to be one percent.

TABLE 6.10 TRAVIS COUNTY POPULATION PROJECTIONS: 1990 TO 2003

Year	People's Population	Growth Rate
1990	576407	
1991	586899	1.82%
1992	593536	1.13%
1993	598734	0.88%
1994	602597	0.65%
1995	606090	0.58%
1996	611525	0.90%
1997	616938	0.89%
1998	622843	0.96%
1999	628881	0.97%
2000	634451	0.89%
2001	641037	1.04%
2002	645876	0.75%
2003	650435	0.71%
		Average = 0.93%

Source: Ref 42

To summarize, this study will use one percent as the vehicle growth rate in Austin, based on the consideration of the growth of buses and trucks. So far, basic parameters and data of buses and the truck traffic on bus routes have been expounded and developed for further studies. The evaluation of the impact of CNG buses will be presented in two chapters: one for evaluating the pavement consumption, and the other for evaluating the rehabilitation cost increases. Chapter 7 will begin the first part of these evaluations.

CHAPTER 7. THE IMPACT OF CNG BUS OPERATIONS ON STREET PAVEMENT

In this chapter, the increase of pavement damage on bus routes and on the entire bus route system under CNG fueled bus operations will be estimated. According to the relationship between axle loading and pavement deterioration developed by the AASHO road test (1958-1961), pavement damage is explained by the number of ESALs applied in the analysis period. The increase of pavement damage can be estimated in terms of the ESAL increase.

In order to carry out this evaluation, several bus routes were chosen as pilot routes for this purpose. The routes chosen were the IF bus route, FW bus route, #1 bus route, and the UT J.J. Jake Pickle Research Center (PRC) services bus line. The ADT for these routes was taken from the 1992 Traffic Map of Travis County, Texas (Ref 37). Numbers of bus applications were determined according to the bus schedule published by Capital Metro (Ref 43). Two special parameters called "ESAL-lane-mile" and "the weighted mean ESAL" were developed by this study to carry out the evaluation.

ESAL-LANE-MILE AND THE WEIGHTED MEAN ESAL

An ESAL calculated for a road only represents the load applied on a certain point of the road. If pavement structure, traffic volume, and other conditions are approximately the same in a length of pavement section, the ESAL value can be used to explain the damage level of the whole section. For an entire bus route, however, since there could be a number of sections with different ESALs, using a simple average ESAL value to explain the damage level for the entire bus route would be inappropriate and unreasonable because of varying section lengths of the routes. In other words, a short section with high ESAL value cannot be weighted the same as a long section with the same ESALs.

To estimate a damage level for an entire bus route with different section lengths, the term ESAL-lane-mile may be used. An ESAL-lane-mile is the ESALs multiplied by the length of a section upon which the ESALs act. It is a parameter combining both ESAL and the length being affected. ESAL-lane-mile is a measurement of the effect of a number of ESALs on a length of a bus lane. For instance, 10 ESAL-lane-miles means 10 ESALs of 18-kip acting on a one-mile length of lane or two ESALs of 18-kip acting on five miles of lane. Dividing the total ESAL-lane-mile by the total length of the route gives the weighted mean ESAL. Use of the weighted mean

ESAL to compare different routes will be more effective. Both parameters are expressed in the following formulas.

$$\text{ESAL-lane-mile}_{(\text{section } i)} = \text{ESAL}_{(i)} \times L_{(i)} ;$$

$$\text{Total ESAL-lane-mile} = \Sigma\, (\text{ESAL}_{(i)} \times L_{(i)}) ;$$

$$\text{The weighted mean ESAL} = \Sigma\, (\text{ESAL}_{(i)} \times L_{(i)}) \,/\, \Sigma(L_{(i)}) .$$

Where

"i" is the section No., "$L_{(i)}$" is the length of section "i" in mile.

CALCULATION OF TRUCK ESALS

Since there are many types of trucks with various loading situations on the roadway, it is difficult to accurately determine truck ESALs if they are calculated in terms of the truck type or the rated truck gross weight. This work may be done by analyzing truck weigh-in-motion data. For the purpose of this study, however, such data were unavailable and an average truck ESAL factor, as recommended in a Project Level User's Manual (Ref 44), is used to determine truck ESAL calculations for Austin. The ESAL factor for average city trucks is taken as follows:

1)	For major arterial streets	ESAL per truck	= 0.8
2)	For minor arterial streets	...	= 0.6
3)	For collector streets	...	= 0.5
4)	For local residential streets	...	= 0.4.

Since trucks often use the side lane, the lane distribution factor for the design lane (the side lane) can be as much as 100 percent. The number of trucks and truck ESALs on the design lane can be calculated as follows:

Number of Trucks on design lane = ADT x (percent truck in ADT) x 50 percent x 100 percent.

ESAL of trucks on design lane = (Number of trucks on design lane) x (ESAL/per truck)

TYPES OF DIESEL AND CNG FUELED BUSES

Types of buses that are used on each bus route is important for the determination of bus ESALs, because different types of buses have different ESAL factors due to various bus weight and seating capacities. As previously noted, the buses operated on fixed bus routes in Austin are predominantly GILLIG diesel fueled buses, accounting for about 80 percent of the total buses in 1993 when CNG fueled buses were not used. Since GILLIG 1100 and GILLIG 1000 have the same axle loads of GVWR, the diesel fueled buses can be simplified to three types, GILLIG 1100, 1700, and 1600. The GILLIG 1100 is the largest diesel bus operated in the system.

According to information provided by the Division of Planning of Capital Metro, the type of bus used for each bus route may be changed due to any specific situation in the bus operation, but principally, the type of bus used for a bus route is fixed based on passenger demands on the route. The following are bus routes in three groups, using GILLIG 1100 (or 1000), GILLIG 1700, and GILLIG 1600, respectively.

Bus routes which use GILLIG 1100 (or 1000) buses are #1/13, #3/17, #25, #4, #18, #6, #37, #38, #8, LX, PX, IF, FW, CR, RR, EC, #40, LA, SR, PV, and WC.

Bus routes which use GILLIG 1700 are #2, #10, #28, #26, #30, #7, #29, #27, #12, #20, #15/16, #5, ER, DE, and NR.

Bus routes which use GILLIG 1600 are #9/14, #19, #29, #21, #22, #32, #33, #42, #61, #62, #64, #65, #66, and #67.

The first group of bus routes consists of the most dense lines in Austin. Most of the UT shuttle bus lines use the GILLIG 1100. Only the ER, DF, and NR bus lines use the GILLIG 1700, which has nearly one-fifth less seating capacity than GILLIG 1100.

Passenger occupancy is another aspect affecting bus ESAL calculation. For a reasonable analysis regarding a route section, both the passenger occupancy and the trend of passenger occupancy should be considered. Generally, high passenger occupancy values should be assigned to sections in the downtown area, and low values should go to route sections in the outer areas of the city. In this study, passenger occupancy for a specific section is based on the mean occupancy at the section of a bus route obtained from statistical analysis of Capital Metro survey data. For most of the sections involved in this analysis, the mean passenger occupancy used in calculating bus ESALs is around 10 to 15 passengers, which is about one-fourth to one-third of the seating capacity of a standard bus. The range is from five to 25.

Since buses always run on the side lane of streets (boarding and deboarding) the lane distribution factor of buses for the design lane, which is the side lane, is assumed to be 100 percent. Structural number (SN) of flexible pavements and the minimum acceptable serviceability (PSI) level, Pt, should be assumed in advance of the ESAL calculation. For a dry, no-freeze region with medium traffic and under 75 percent reliability, the SN and Pt are assumed as follows (Ref 33):

SN = 2.5, Pt = 2.0 for collector and residential streets,

SN = 3.0, Pt = 2.5. for arterial streets.

The number of buses and the ESAL of buses on the design lane are calculated as follows:

Number of Buses on design lane = Σ[Bus(i) in one direction] x 100 percent,

ESAL of buses on design lane = Σ[Number of Bus(i) x ESAL per bus(i)].

Where: Bus(i) indicates the ID number and type of buses that share the same lane of a bus route. The ESAL per bus(i) is the ESAL factor of the bus(i), and it should be determined based on a) the bus type, b) the trend of occupancy of the route, c) the mean occupancy, and d) the SN and Pt relative to street category. Table 7.1 lists the ESAL factors for different types of buses under different passenger occupancies. Bus ESAL factors under other Pt and SN values can be found in Appendix 1.

TABLE 7.1 ESAL (EQUIVALENT SINGLE AXLE LOAD) FACTOR FOR DIFFERENT BUSES

Occu-pancy	TMC CNG Bus		GILLIG 1100 bus		GILLIG 1700 bus		GILLIG 1600 bus		Blue Bird CNG bus		Trolly 900 Dillo	
	Pt= 2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.0
	SN= 2.5	3.0	2.5	3.0	2.5	3.0	2.5	3.0	2.5	3.0	2.5	2.5
0	1.349	1.347	1.292	1.287	1.040	1.057	0.970	0.987	0.830	0.872	0.213	0.276
5	1.494	1.476	1.433	1.411	1.158	1.163	1.081	1.087	0.929	0.963	0.244	0.313
10	1.653	1.615	1.586	1.544	1.287	1.277	1.203	1.195	1.038	1.062	0.279	0.354
15	1.824	1.764	1.751	1.688	1.427	1.401	1.335	1.311	1.156	1.169	0.317	0.398
20	2.009	1.923	1.930	1.842	1.579	1.533	1.479	1.436	1.285	1.284	0.360	0.446
25	2.210	2.095	2.124	2.008	1.744	1.676	1.635	1.571	1.425	1.408	0.408	0.498
30	2.425	2.278	2.333	2.185	1.922	1.829	1.804	1.717	1.577	1.541	0.461	0.555

TABLE 7.1 ESAL (EQUIVALENT SINGLE AXLE LOAD) FACTOR FOR DIFFERENT BUSES
(Continued)

Occu-pancy	TMC CNG Bus		GILLIG 1100 bus		GILLIG 1700 bus		GILLIG 1600 bus		Blue Bird CNG bus		Trolly 900 Dillo	
	Pt= 2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.5	2.0	2.0
	SN= 2.5	3.0	2.5	3.0	2.5	3.0	2.5	3.0	2.5	3.0	2.5	2.5
35	2.658	2.474	2.558	2.375	2.115	1.994	1.987	1.873	1.742	1.685	0.519	0.617
40	2.908	2.684	2.800	2.578	2.323	2.170	2.184	2.040	1.921	1.839	0.582	0.683
45	3.176	2.908	3.060	2.795	2.547	2.359	2.397	2.219	2.114	2.004	0.653	0.754
50	3.464	3.147	3.339	3.027	2.788	2.561			2.322	2.181	0.730	0.831
55	3.773	3.402	3.639	3.274	3.047	2.777			2.546	2.371		
60	4.103	3.673	3.959	3.538	3.325	3.008			2.788	2.573		
65	4.456	3.962	4.302	3.819								
70			4.668	4.117								

Note: Occupancy expressed as number of passengers.

PILOT STUDY ON CNG BUS IMPACTS

In order to explore the impact on pavement damage of CNG bus operation, four bus routes were chosen as pilot routes for the study. They are:

1) IF bus route (UT shuttle bus). This bus runs every four to six minutes during the day. Total repetitions in a weekday are about 158. The GILLIG 1100 diesel bus is used on this line.

2) FW bus route (UT shuttle bus). This bus runs every six to eight minutes during the day. Total repetitions in a weekday are about 105. The GILLIG 1100 diesel bus is used on this line.

3) UT PRC service bus line. This bus runs every 30 minutes between the main campus and UT PRC. Total repetitions in a weekday are about 22. Currently the Blue Bird CNG bus is operating on this line.

4) #1 bus route (Capital Metro bus). This bus runs every 10 minutes during the day. Total repetitions in a weekday are about 84. The GILLIG 1100 diesel bus is used on this line.

Each bus route is divided into a number of sections based on location, street category, ADT volume, and load applications. Portions of the FW and PRC routes which are on Mopac (Loop 1) are excluded in this analysis because freeways are not within the scope of the study.

One important characteristic of the bus route system is that routes join at the central area of the city and share the major streets of the city. Therefore, when counting bus applications for a specific route section, one should carefully count the bus lines that share the same route. For instance, as many as 14 bus lines share 11th Street in front of the Capitol Building. In addition, bus repetitions may also be different in two directions of a roadway. The largest group on the two directions should be chosen for computing the number of bus repetitions.

In this chapter, the ESAL, ESAL-lane-mile, and weighted mean ESAL are based on a 24-hour weekday. Numbers of bus repetitions are calculated from a weekday schedule since ADT volume used in this analysis was based on 24-hour weekday axle counts.

Pilot Study on IF Bus Route

The IF bus route has a length of about 3.018 lane miles and contains 13 sections. A map of the route and its sections is shown in Figure 7.1. For simplification, lengthy and tedious calculations in the pilot study are omitted here. However, input data and outputs of the study processes are shown in Appendix 2, respectively, which includes: a) buses and trucks applied on each section of the IF route; b) ESALs under diesel bus uses on IF route (one direction); and c) ESALs under CNG bus uses on IF route (one direction).

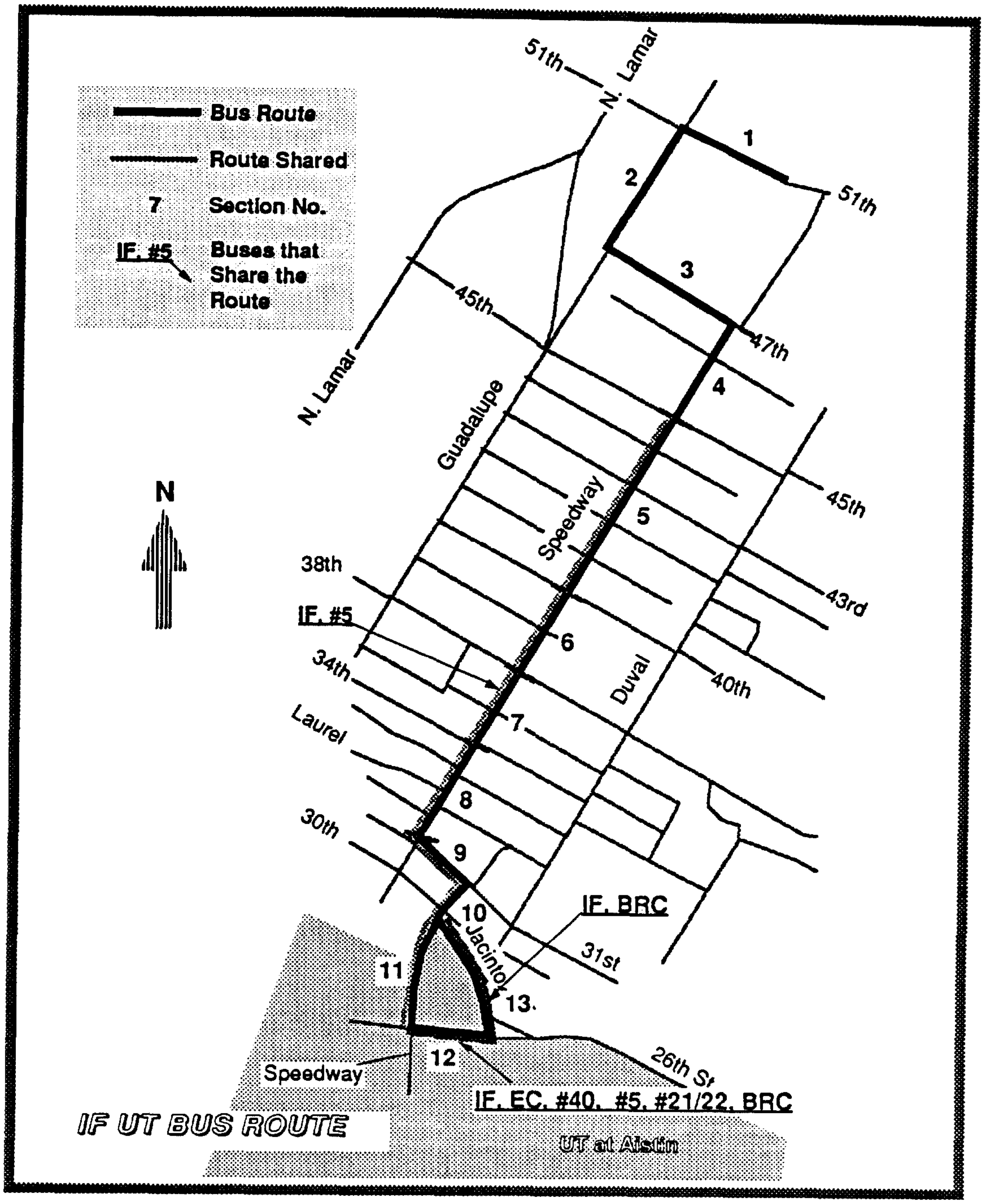


Fig 7.1 The IF Bus Route

Results of a comparison study on uses of diesel and CNG buses are shown in Table 7.2, which are the essential outputs of the study for the IF bus route. The results can be summarized as follows:

1) On average, 96 percent of the ESALs applied on the IF route are contributed by axle loading of buses. In contrast, the ESALs of trucks are only four percent (on average) of the total ESALs in the section indicating how important the bus load is to pavements on the bus routes.

2) For diesel bus operations with normal traffic volume, the total ESAL-lane-miles = 1049.92. The weighted mean ESAL = 1049.92 / 3.018 = 347.886 (ESALs).

3) For CNG bus operations with normal traffic volume, the total ESAL-lane-mile = 1113.97. The weighted mean ESAL = 1113.97 / 3.018 = 369.109 (ESALs).

The increase of pavement damage which can be explained as a percentage increase of the number of ESALs for the entire IF bus route under CNG bus applications is presented below:

Percent increase of ESAL = (369.109 - 347.886) / 347.886 = 6.1 percent.

TABLE 7.2 COMPARISON OF CNG BUS AND DIESEL BUS USES ON IF BUS ROUTE

Section ID Number	Length (mile)	ADT Volume	ESAL under Diesel Bus Application	ESAL-lane-mile under Diesel Application	ESAL under CNG Bus Application	ESAL-lane-mile under CNG Application	ESAL Increase % due to CNG Application
1	0.21	11120	248.64	52.21	258.36	54.25	**3.91%**
2	0.308	6890	264.32	81.41	274.91	84.67	**4.00%**
3	0.308	1930	252.86	77.88	263.44	81.14	**4.19%**
4	0.225	1930	254.40	57.24	264.99	59.62	**4.16%**
5	0.438	4110	310.13	135.83	335.01	146.74	**8.03%**
6	0.2	5260	338.59	67.72	364.40	72.88	**7.62%**
7	0.19	5260	366.89	69.71	393.67	74.80	**7.30%**
8	0.225	5960	404.35	90.98	433.38	97.51	**7.18%**
9	0.131	6280	404.99	53.05	434.02	56.86	**7.17%**
10	0.078	6280	404.99	31.59	434.02	33.85	**7.17%**
11	0.275	6280	404.99	111.37	434.02	119.35	**7.17%**
12	0.133	24100	798.91	106.26	854.28	113.62	**6.93%**
13	0.297	11110	386.08	114.67	399.60	118.68	**3.50%**
Σ	**3.018**			**1049.92**		**1113.97**	

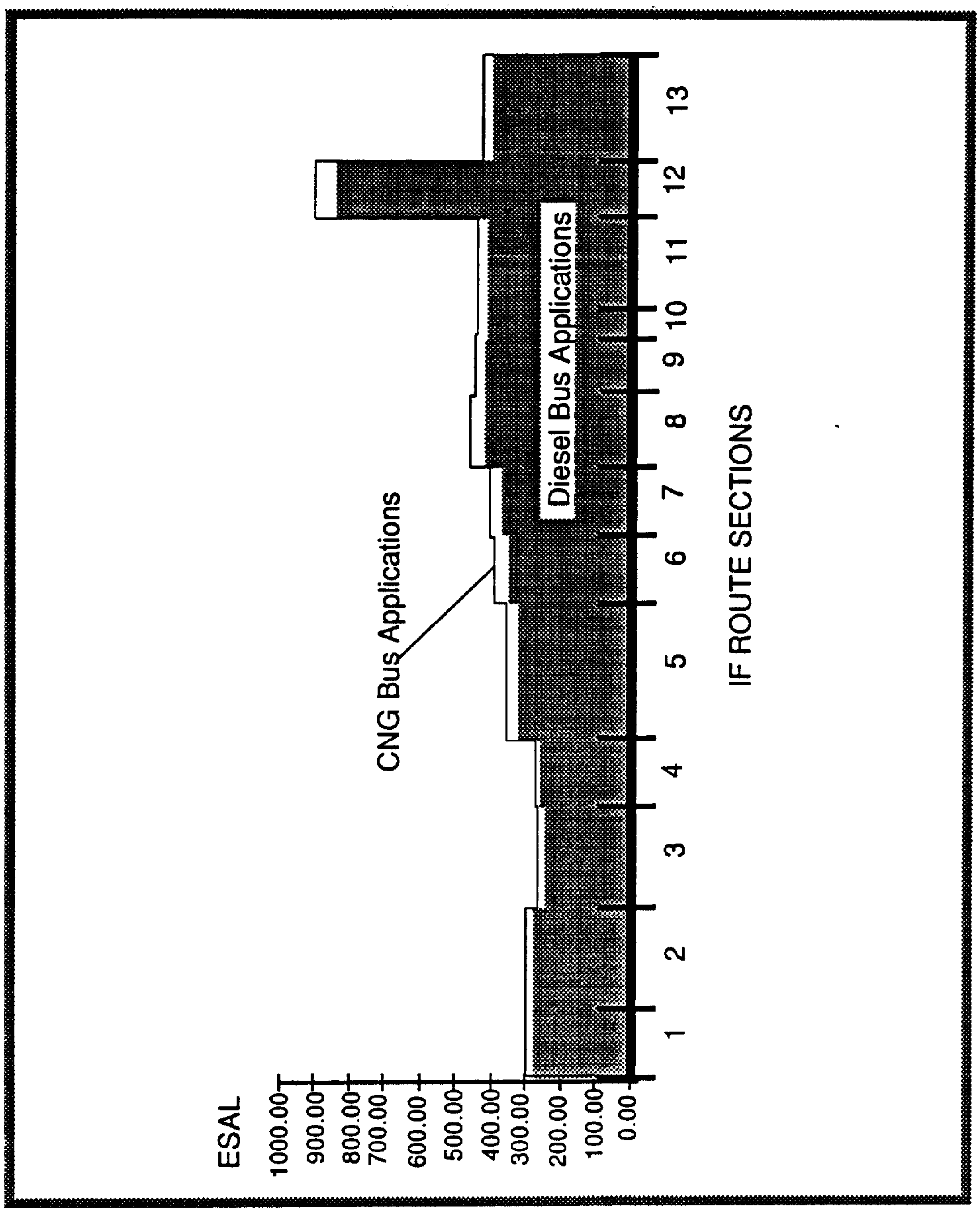


Fig 7.2 ESAL value at each section of IF Route

Figure 7.2 is a visual comparison of damage levels due to diesel buses and CNG buses operating on the IF bus route. The heights of the dark area in Figure 7.2 show the values of ESAL for each section under diesel bus uses. The solid line on the top of the dark area shows the ESAL values of each section under CNG bus uses. Thus, white gaps between the dark area and the solid line indicate the increase of ESALs for each section along the bus route due to CNG bus uses. Notice that sections five to 12 have the highest ESAL increases in all and greater than 6.1 percent. This indicates that pavement damage in these sections will be higher than the rest of the sections.

Pilot Study on FW Bus Route

FW bus route has a length of about 4.561 lane miles and 14 sections shown in Figure 7.3. Again, input data and outputs are shown in Appendix 3, which includes a) the number of buses and trucks applied on each section, b) ESALs under diesel bus uses (one direction), and c) ESALs under CNG bus uses (one direction). Table 7.3 shows the results of a comparison study on uses of diesel buses and CNG buses on the FW bus route and are summarized as follows:

1) On average, 87 percent of the ESALs applied on the FW route are contributed by buses. Trucks only contributed 13 percent (on average) of the total ESALs in the section.
2) For diesel bus operations with normal traffic volume, total ESAL-lane-miles = 1571.28. The weighted mean ESAL = 1571.28 / 4.561 = 344.50 (ESALs).
3) For the CNG bus operations with normal traffic volume, total ESAL-lane-miles = 1685.75. The weighted mean ESAL = 1685.75 / 4.561 = 369.60 (ESALs).

The increase of pavement damage which can be explained as a percentage increase of the number of ESALs for the entire FW bus route under CNG bus applications is

Percent increase of ESAL = (369.60 - 344.50) / 344.50 = 7.3 percent.

A visual comparison of diesel bus uses and CNG bus uses on FW bus route is given on Figure 7.4. White gaps between the dark area and the solid line indicate the increase of ESALs for each section along the bus route due to use of CNG buses. Notice that sections three and four, and especially sections six to twelve have higher ESAL increases than the rest of the sections. This indicates that more pavement damage will occur in these sections.

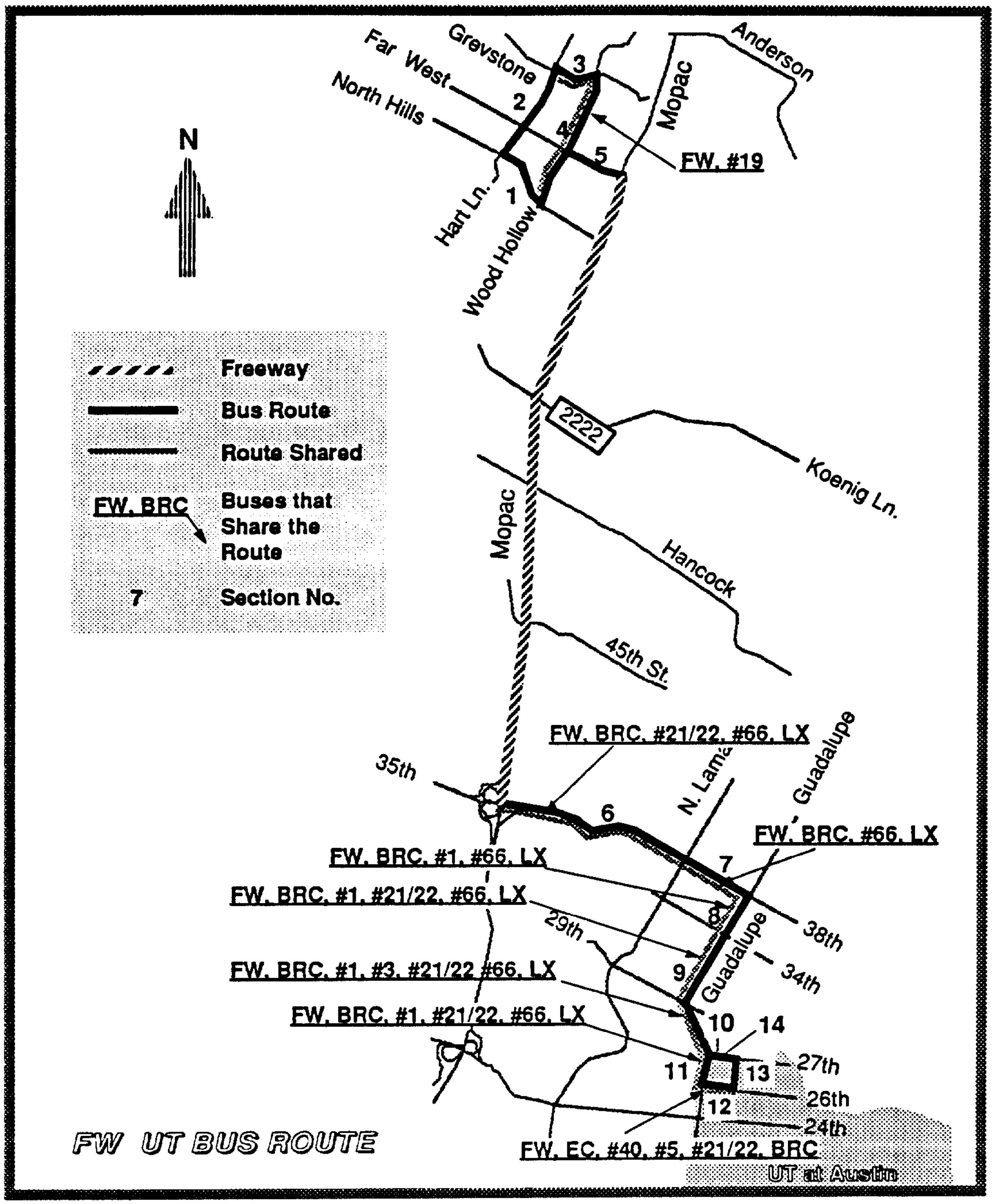


Fig 7.3 FW Bus Route

TABLE 7.3 COMPARISON OF CNG BUS AND DIESEL BUS APPLICATION ON FW BUS ROUTE

Section ID Number	Length (mile)	ADT volume	ESAL under Diesel Bus Application	ESAL-lane-mile under Diesel Application	ESAL under CNG Bus Application	ESAL-lane-mile under CNG Application	ESAL Increase % due to CNG Application
1	0.277	6200	173.94	48.18	180.97	50.13	4.04%
2	0.469	5910	173.59	81.41	180.63	84.71	4.05%
3	0.213	5600	203.29	43.30	221.57	47.19	8.99%
4	0.656	7950	206.11	135.21	224.39	147.20	8.87%
5	0.291	30630	299.75	87.23	307.71	89.54	2.66%
6	0.906	30180	414.48	375.52	449.64	407.37	8.48%
7	0.342	27650	347.37	118.80	372.01	127.23	7.09%
8	0.19	25070	508.28	96.57	540.22	102.64	6.28%
9	0.388	25790	539.78	209.44	582.24	225.91	7.87%
10	0.255	26120	540.77	137.90	583.23	148.72	7.85%
11	0.153	30360	583.85	89.33	626.31	95.83	7.27%
12	0.134	20690	698.85	93.65	763.66	102.33	9.27%
13	0.153	5720	190.75	29.18	198.39	30.35	4.01%
14	0.134	5720	190.75	25.56	198.39	26.58	4.01%
	4.561			1571.28		1685.75	

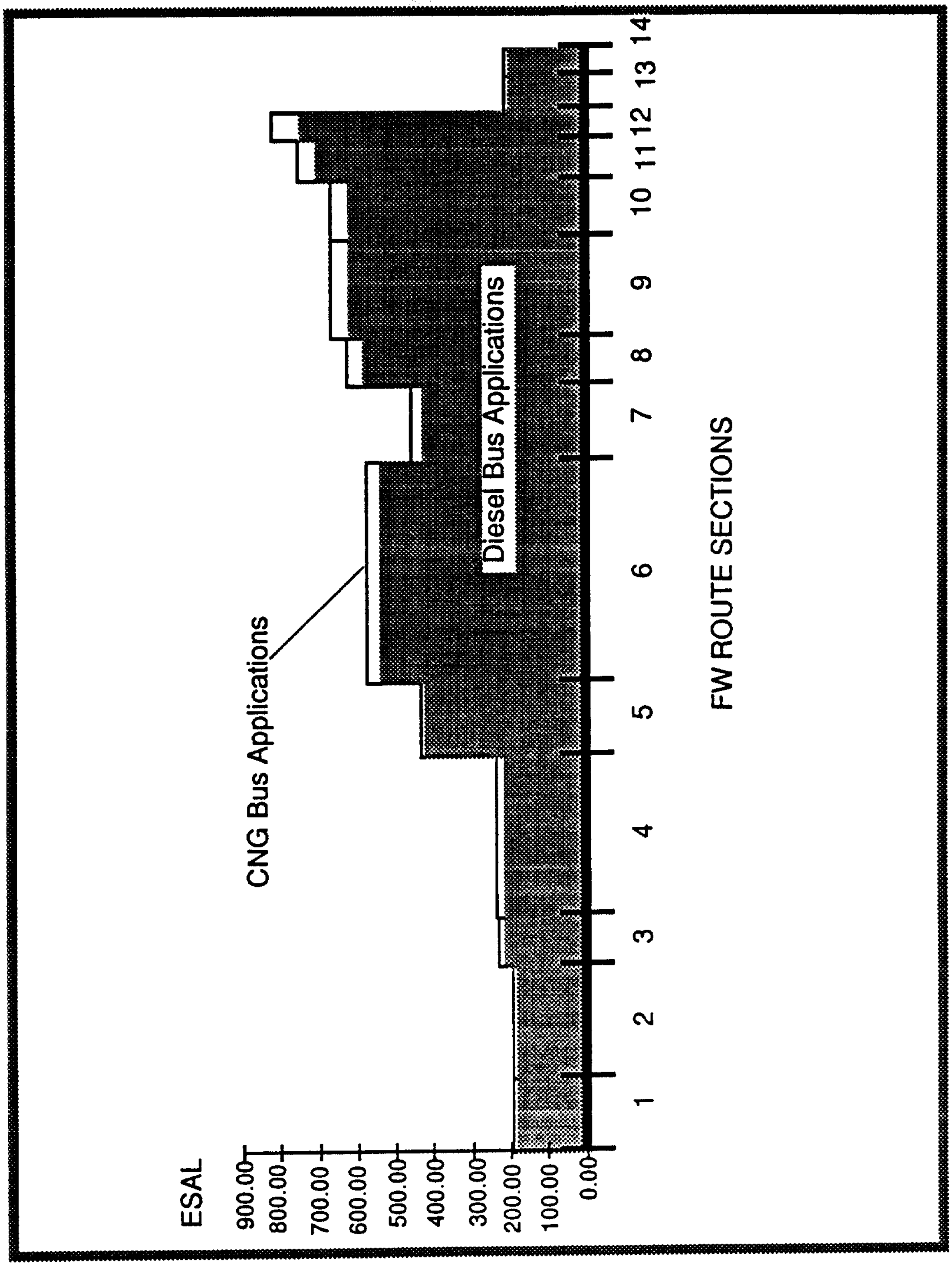


Fig 7.4 ESAL value at each section of FW Bus Route

Pilot Study on PRC Bus Route

The PRC bus route is not a major bus route. Since most of its route is shared with the FW bus, only two sections were chosen to demonstrate the estimation of two different CNG Bus applications, the Blue Bird CNG bus and the TMC CNG bus. The map of the PRC route is shown on Figure 7.5. All the necessary inputs and the output results are shown in Tables 7.4 and 7.5.

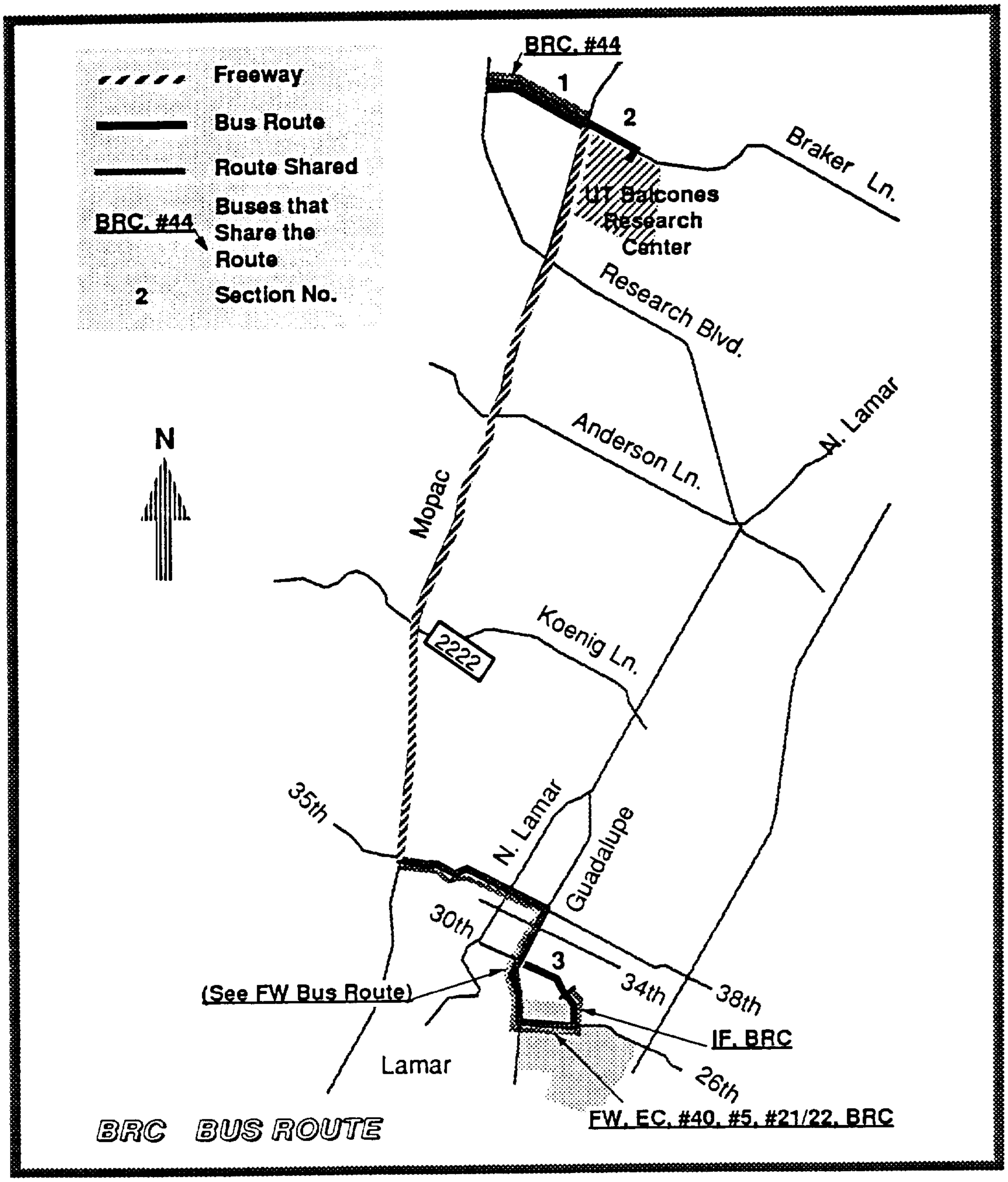


Fig 7.5 PRC Service Bus Route

TABLE 7.4 ESAL UNDER BLUE BIRD CNG BUS OPERATION ON PRC ROUTE (ONE DIRECTION)

Section ID Number	Section Length (mile)	ADT volume	% Truck in ADT	Number of Trucks	Truck ESAL	Number of BRC buses	Bus ESAL	Total ESAL in Section	ESAL-lane-mile in Section
1	0.915	8000	0.8	32	19.2	22	28.27	47.47	43.43
2	0.483	8000	0.8	32	19.2	22	28.27	47.47	22.93
Σ	1.398								66.36

* #44 bus is ignored because of its few repetitions.

TABLE 7.5 ESAL UNDER TMC CNG BUS OPERATION ON PRC ROUTE (ONE DIRECTION)

Section ID Number	Section Length (mile)	ADT volume	% Truck in ADT	Number of Trucks	Truck ESAL	Number of BRC buses	Bus ESAL	Total ESAL in Section	ESAL-lane-mile in Section
1	0.915	8000	0.8	32	19.2	22	44.21	63.41	58.02
2	0.483	8000	0.8	32	19.2	22	44.21	63.41	30.63
Σ	1.398								88.64

* #44 bus is ignored because of its few repetitions.

Results for the two sections of the PRC service line can be summarized as follows:

1) Bus ESALs are higher than truck ESALs on the bus route,
2) For Blue Bird bus applications with normal traffic volume,
   total ESAL-lane-miles = 66.36,
   the weighted mean ESAL = 66.36/1.398 = 47.47 (ESALs),
3) For TMC CNG bus applications with normal traffic volume, total ESAL-lane-miles = 88.64. The weighted mean ESAL = 88.64/1.398 = 63.41 (ESAL).

The increase of pavement damage that can be explained as a percentage increase of the number of ESALs for the entire PRC bus route under TMC CNG Bus applications is

Percent increase of ESAL = (63.41 - 47.47) / 47.47 = 33.6 percent.

Pilot Study on #1 Bus Route

The #1 bus route has a length of about 9.46 lane-miles and contains 20 sections. A map of the route is shown in Figure 7.6.

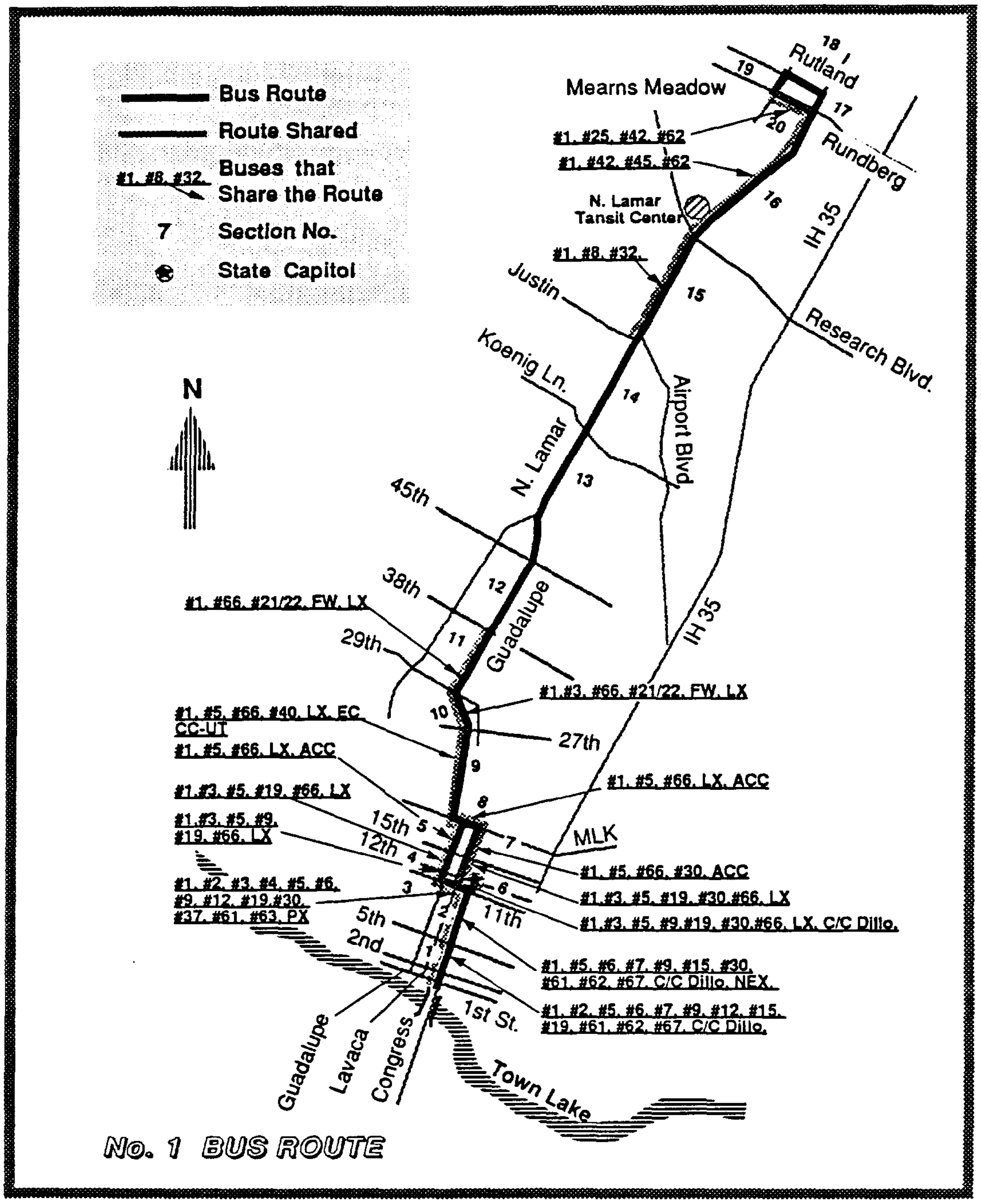


Fig 7.6 #1 Bus Route

For simplification, input and output data of this study are shown in Appendix 4, which includes: a) number of buses and trucks applied on each section of the #1 bus route; b) ESALs under diesel bus uses on #1 bus route (one direction); c) ESALs under uses of CNG buses (remaining diesel Dillo buses) on #1 bus route (one direction); and d) ESALs under CNG bus uses (for all routes) on #1 bus route (one direction).

The #1 bus route is the most dense bus route in Austin. Some sections of the #1 route in the downtown area are shared by more than 10 bus lines. A total of 23 bus lines are involved in the analysis of the #1 bus route. Actually, there are more than 23 bus lines involved; however, some bus lines that have few repetitions were ignored for simplification.

Two alternatives of CNG bus operations are used. One assumes that the TMC CNG bus will be used for all bus lines except the diesel Dillo buses remaining in service. Another assumes that all the bus lines use the TMC CNG buses. Comparison results for these two alternatives are shown in Tables 7.6 and 7.7, respectively.

TABLE 7.6 ALTERNATIVE 1: COMPARISON OF DIESEL BUS AND CNG BUS APPLICATIONS ON #1 BUS ROUTE, ASSUMING THAT THE DIESEL DILLO BUS REMAINS IN SERVICE

Section ID Number	Length (mile)	ADT volume	ESAL under Diesel Bus Application	ESAL-lane-mile under Diesel Application	ESAL under CNG Bus Application	ESAL-lane-mile under CNG Application	ESAL Increase % due to CNG Application
1	0.34	19650	542.26	184.369	622.20	211.548	**14.74%**
2	0.335	19120	415.36	139.146	459.36	153.886	**10.59%**
3	0.223	8660	735.70	164.061	836.67	186.577	**13.72%**
4	0.345	13020	437.44	150.916	485.60	167.53	**11.01%**
5	0.23	9240	314.27	72.2822	337.31	77.5814	**7.33%**
6	0.345	16130	474.67	163.762	524.13	180.823	**10.42%**
7	0.23	9930	359.07	82.5859	393.37	90.474	**9.55%**
8	0.108	24710	394.63	42.6201	417.67	45.1084	**5.84%**
9	0.717	30326	761.97	546.331	801.24	574.488	**5.15%**
10	0.25	26120	538.59	134.648	567.04	141.759	**5.28%**
11	0.58	25790	537.27	311.617	565.72	328.115	**5.29%**
12	0.625	22130	243.26	152.041	250.09	156.309	**2.81%**
13	1.138	30530	276.86	315.072	283.69	322.844	**2.47%**
14	0.93	40820	305.06	283.709	311.43	289.631	**2.09%**
15	0.808	35100	393.35	317.829	399.72	322.974	**1.62%**
16	1.4	37280	304.92	426.882	320.20	448.284	**5.01%**

TABLE 7.6 ALTERNATIVE 1: COMPARISON OF DIESEL AND CNG BUS APPLICATIONS ON #1 ROUTE, ASSUMING THE DIESEL DILLO BUS REMAINS IN SERVICE *(Continued)*

Section ID Number	Length (mile)	ADT volume	ESAL under Diesel Bus Application	ESAL-lane-mile under Diesel Application	ESAL under CNG Bus Application	ESAL-lane-mile under CNG Application	ESAL Increase % due to CNG Application
17	0.13	40170	279.17	36.2922	284.69	37.0096	**1.98%**
18	0.3	15390	180.05	54.0151	185.57	55.6708	**3.07%**
19	0.13	13130	171.01	22.2314	176.53	22.9488	**3.23%**
20	0.3	13130	251.11	75.3319	268.40	80.5196	**6.89%**
Σ	**9.464**			**3675.74**		**3894.08**	

TABLE 7.7 ALTERNATIVE 2: COMPARISON OF DIESEL AND CNG BUS APPLICATIONS ON #1 ROUTE, ASSUMING REPLACEMENT OF ALL DIESEL BUSES BY TMC CNG BUSES

Section ID Number	Length (mile)	ADT volume	ESAL under Diesel Bus Application	ESAL-lane-mile under Diesel Application	ESAL under CNG Bus Application	ESAL-lane-mile under CNG Application	ESAL Increase % due to CNG Application
1	0.34	19650	542.26	184.369	701.04	238.354	**29.28%**
2	0.335	19120	415.36	139.146	538.20	180.298	**29.57%**
3	0.223	8660	735.70	164.061	836.67	186.577	**13.72%**
4	0.345	13020	437.44	150.916	485.60	167.53	**11.01%**
5	0.23	9240	314.27	72.2822	422.83	97.2517	**34.54%**
6	0.345	16130	474.67	163.762	602.97	208.024	**27.03%**
7	0.23	9930	359.07	82.5859	478.89	110.144	**33.37%**
8	0.108	24710	394.63	42.6201	503.19	54.3449	**27.51%**
9	0.717	30326	761.97	546.331	873.40	626.227	**14.62%**
10	0.25	26120	538.59	134.648	567.04	141.759	**5.28%**
11	0.58	25790	537.27	311.617	565.72	328.115	**5.29%**
12	0.625	22130	243.26	152.041	250.09	156.309	**2.81%**
13	1.138	30530	276.86	315.072	283.69	322.844	**2.47%**
14	0.93	40820	305.06	283.709	311.43	289.631	**2.09%**
15	0.808	35100	393.35	317.829	399.72	322.974	**1.62%**
16	1.4	37280	304.92	426.882	320.20	448.284	**5.01%**
17	0.13	40170	279.17	36.2922	284.69	37.0096	**1.98%**
18	0.3	15390	180.05	54.0151	185.57	55.6708	**3.07%**
19	0.13	13130	171.01	22.2314	176.53	22.9488	**3.23%**
20	0.3	13130	251.11	75.3319	268.40	80.5196	**6.89%**
Σ	**9.464**			**3675.74**		**4074.82**	

Results from this study can be summarized as follows:

1) On average, 76 percent of ESALs applied on the sections of #1 route are contributed by buses. The ESALs of trucks on bus route #1 are only about 24 percent (on average) of the total ESALs.
2) For diesel bus operations with normal traffic volume, total ESAL-lane-miles = 3675.74. The weighted mean ESAL = 3675.74/9.464 = 388.39 (ESALs).
3) For alternative-1 CNG bus operations with normal traffic volume, total ESAL-lane-miles = 3894.08. The weighted mean ESAL = 3894.08/9.464 = 411.46 (ESALs).
4) For alternative-2 CNG bus operations with normal traffic volume, total ESAL-lane-miles = 4074.82. The weighted mean ESAL = 4074.82/9.464 = 430.56 (ESALs).

The increase of pavement damage explained as a percentage increase of the number of ESALs for the entire #1 bus route is:

If all bus lines use CNG buses except the Dillo bus lines, then
Percent increase of ESALs = (411.46 - 388.39) / 388.39 = 5.9 percent.

If all bus lines, including the Dillo bus lines, use CNG buses , then
Percent increase of ESALs = (430.56 - 388.39) / 388.39 = 10.9 percent.

A visual comparison of the diesel bus operations and CNG bus operations is illustrated in Figure 7.7. It can be seen from this graph that sections 1 to 9 have very high percentages of ESAL increase. These sections are in downtown Austin, the busiest area of the city. As mentioned before, the #1 bus route is the most dense bus line in the city and these sections are likewise the most dense segments of the #1 bus route.

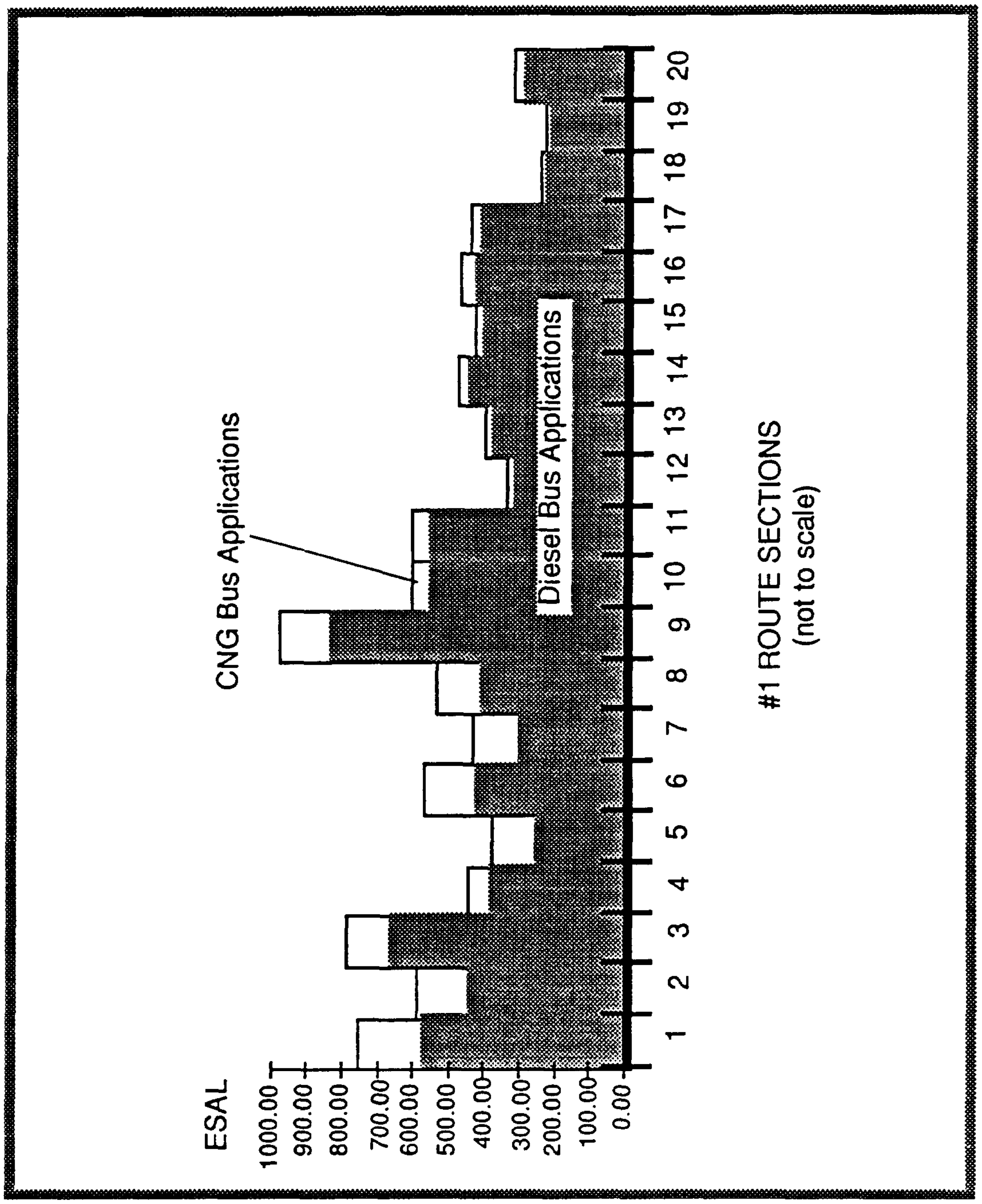


Fig 7.7 ESAL at sections of #1 Bus Route (if all bus lines use CNG buses)

EVALUATION OF THE IMPACT ON THE ENTIRE ROUTE SYSTEM IN AUSTIN

This study is based on total lane miles data recorded by the Planning Division of Capital Metro, Austin (Ref 45). Total lane miles run by all the buses operated on each fixed route on a workday basis were reported. Both UT shuttle bus and Metro bus routes, comprising nearly 60 bus lines, were included. Since passenger demands for each route are different, the buses assigned for each route are also different in seating capacity. The ESALs per bus are determined based on the type of bus operated on each route and the average passenger occupancy within each route. Multiplying the ESALs per bus of the bus type by the total lane miles in the line report, the ESAL-lane-mile of each bus route can be obtained:

Total ESAL-lane-miles (of the entire route system) =

$$\Sigma\,[\text{ ESAL per bus (i) x Total lane mile (i)}].$$

where

i = 1, 2, ..., n, indicating that there are n bus routes in the route system.

ESALs per bus (i) is the ESALs of the type of bus operated in route (i). The type of CNG bus for all routes is the TMC CNG bus. Total lane-mile(i) is the total lane miles run by the buses of route (i) reported in a workday. The Street and Bridge Division of the City of Austin estimates that there are about 960 lane miles of fixed bus routes within about 5,000 lane miles of streets in the city (Ref 46). Dividing the total ESAL-lane-miles calculated using the above equation for the route system by 960 (lane miles), the weighted mean ESAL of the entire route system can be obtained. A comparison of CNG buses vs. diesel buses for the system can then be carried out.

In Table 7.8, the 6th and 8th columns from the left show the calculated [ESAL per bus (i) x Total lane mile (i)] of CNG bus and diesel bus operation for each route, respectively. The calculated total ESAL-lane-miles (of the entire route system) of the two compared fuels are shown at the bottom of the table. Using these data, the expected results can be easily obtained.

TABLE 7.8 ESAL-LANE-MILES OF EACH ROUTE UNDER DIESEL BUS APPLICATION AND CNG BUS APPLICATION

ID Number of Bus Route	Bus Type	Average Occu-pancy	Total Lane-Mile (i)	ESAL/ per bus(i) of diesel bus	ESAL-lane-mile(i) under diesel bus applic.	ESAL/ per bus(i) of CNG bus	ESAL-lane-mile(i) under CNG bus applic.
1	GILLIG 1100	15	2262.30	1.7513	3961.97	1.8241	4126.66
2	GILLIG 1700	10	1018.90	1.2867	1311.02	1.6527	1683.94
3	GILLIG 1100	15	1592.90	1.7513	2789.65	1.8241	2905.61
4	GILLIG 1100	15	1264.10	1.7513	2213.82	1.8241	2305.84
5	GILLIG 1700	10	1474.50	1.2867	1897.24	1.6527	2436.91
6	GILLIG 1100	15	524.60	1.7513	918.73	1.8241	956.92
7	GILLIG 1700	10	2377.90	1.2867	3059.64	1.6527	3929.96
8	GILLIG 1100	15	1537.20	1.7513	2692.10	1.8241	2804.01

TABLE 7.8 ESAL-LANE-MILES OF EACH ROUTE UNDER DIESEL BUS APPLICATION AND CNG BUS APPLICATION *(Continued)*

ID Number of Bus Route	Bus Type	Average Occu-pancy	Total Lane-Mile (i)	ESAL/ per bus(i) of diesel bus	ESAL-lane-mile(i) under diesel bus applic.	ESAL/ per bus(i) of CNG bus	ESAL-lane-mile(i) under CNG bus applic.
9	GILLIG 1700	10	664.00	1.2867	854.37	1.6527	1097.39
12	GILLIG 1600	5	1604.70	1.0812	1735.00	1.4944	2398.06
15	GILLIG 1700	10	1075.60	1.2867	1383.97	1.6527	1777.64
19	GILLIG 1600	5	778.60	1.0812	841.82	1.4944	1163.54
21	GILLIG 1600	5	443.40	1.0812	479.40	1.4944	662.62
22	GILLIG 1600	5	443.40	1.0812	479.40	1.4944	662.62
25	GILLIG 1100	15	511.00	1.7513	894.91	1.8241	932.12
28	GILLIG 1700	10	496.40	1.2867	638.72	1.6527	820.40
30	GILLIG 1700	10	547.60	1.2867	704.60	1.6527	905.02
32	GILLIG 1600	5	539.80	1.0812	583.63	1.4944	806.68
33	GILLIG 1600	5	715.90	1.0812	774.03	1.4944	1069.84
37	GILLIG 1100	15	1352.40	1.7513	2368.46	1.8241	2466.91
42	GILLIG 1600	5	131.00	1.0812	141.64	1.4944	195.77
61	GILLIG 1600	5	99.10	1.0812	107.15	1.4944	148.10
62	GILLIG 1600	5	162.50	1.0812	175.70	1.4944	242.84
64	GILLIG 1600	5	78.60	1.0812	84.98	1.4944	117.46
65	GILLIG 1600	5	116.40	1.0812	125.85	1.4944	173.95
69	GILLIG 1600	5	92.00	1.0812	99.47	1.4944	137.48
85	DILLO	10	380.60	0.2786	106.04	1.6527	629.02
86	DILLO	10	384.00	0.2786	106.98	1.6527	634.64
87	DILLO	10	431.20	0.2786	120.13	1.6527	712.64
71-LX	GILLIG 1100	15	2228.80	1.7513	3903.30	1.8241	4065.55
79-PX	GILLIG 1100	15	342.60	1.7513	600.00	1.8241	624.94
14	GILLIG 1100	15	141.20	1.7513	247.28	1.8241	257.56
42	GILLIG 1600	5	458.80	1.0812	496.05	1.4944	685.63
RR	GILLIG 1100	15	578.60	1.7513	1013.30	1.8241	1055.42
WC	GILLIG 1100	15	609.20	1.7513	1066.89	1.8241	1111.24
CR	GILLIG 1100	15	1488.90	1.7513	2607.51	1.8241	2715.90
ER	GILLIG 1700	10	639.60	1.2867	822.97	1.6527	1057.07
FORTY	GILLIG 1100	15	265.90	1.7513	465.67	1.8241	485.03
FW	GILLIG 1100	15	1712.40	1.7513	2998.93	1.8241	3123.59
IF	GILLIG 1100	15	868.10	1.7513	1520.30	1.8241	1583.50
LA	GILLIG 1100	15	955.80	1.7513	1673.89	1.8241	1743.47

TABLE 7.8 ESAL-LANE-MILES OF EACH ROUTE UNDER DIESEL BUS APPLICATION AND CNG BUS APPLICATION *(Continued)*

ID Number of Bus Route	Bus Type	Average Occu-pancy	Total Lane-Mile (i)	ESAL/ per bus(i) of diesel bus	ESAL-lane-mile(i) under diesel bus applic.	ESAL/ per bus(i) of CNG bus	ESAL-lane-mile(i) under CNG bus applic.
NR	GILLIG 1700	10	720.20	1.2867	926.68	1.6527	1190.27
PV	GILLIG 1100	15	1680.00	1.7513	2942.18	1.8241	3064.49
EC	GILLIG 1100	15	470.00	1.7513	823.11	1.8241	857.33
Σ					16861.45		17987.32

Note: The ID number of 31, 39, 40, 43, 44, 45, 63, 102-LAGO, 103-LAGO buses are ignored from the comparison study due to less importance and very few applications.

The results of this comparison are the following:

The weighted mean ESAL for the entire route system under diesel bus operations is

$$16861.45/960 = 17.6.$$

The weighted mean ESAL for the entire route system under CNG bus operations is

$$17987.32/960 = 18.7.$$

The increase in ESALs on the entire bus route system under CNG bus operations is

$$(18.737 - 17.564)/17.564 = 6.7 \text{ percent.}$$

This comparison is based on buses acting alone on bus routes. Associated truck traffic which may contribute 15 percent of total ESALs was not considered in this evaluation.

In this chapter, impacts as a percent increase of ESALs on pavements of three pilot routes and on the entire route system are estimated. These results may be used as valuable references for the estimation of other routes. The impact on costs of pavement rehabilitation is the other major task of this study, which will be carried out in the next chapter.

CHAPTER 8 . IMPACT OF CNG FUELED BUS OPERATIONS ON PAVEMENT REHABILITATION COSTS

INTRODUCTION

Since the use of CNG fueled buses will increase pavement consumption due to increased ESAL applications on streets, it is reasonable to predict that pavement rehabilitation costs will also increase. For practical purposes, it is important to provide a numerical solution to show the cost increases, or how much the CNG bus operations increase the cost of street pavement rehabilitation.

Cost in this chapter represents only the rehabilitation cost, including the delay time costs for users due to rehabilitation construction. In other words, this is not an entire life-cycle cost analysis. Also, since the major concern of this study is a comparison of two costs (diesel bus and CNG bus operation), rehabilitation methods are not specifically considered. A common rehabilitation method, pavement overlay, is used.

For consistency, the impacts in this chapter will be evaluated by calculating percent increase of the rehabilitation cost in a 20-year design period. Since pavement condition varies among sections of streets, overlay rehabilitation strategy for a specific section could be one of several alternatives, and since the unit costs of construction change, use of a dollar value for evaluation of impact will complicate the issue. By contrast, using percent increase, a relative value, to estimate the impact is simple and will lead to a general solution applicable to a variety of situations.

The computer program for overlay design used in this study is called MPRDS-1 (Municipal Pavement Rehabilitation Design System Version 1.0). Although the program itself is fundamentally sound and reliable, appropriate inputs must be carefully chosen and the results interpreted. Input parameters for the overlay design and the MPRDS-1 program itself will be described in later sections. The SAS (Statistical Analysis System) program is used to process the cost results to obtain an estimation model.

Two results of the cost analysis will be given in this chapter. First are the results of the three pilot routes, including the weighted average percent cost increase and ranges of the percent cost increase. These results provide useful references and scales for pavement engineers and urban transportation planners to evaluate the impact on pavement rehabilitation cost under CNG bus operation. Second, through statistical analysis on a group of sections, a regression model will be given, which will enable readers to estimate the increase of rehabilitation cost for any pavement section without doing complicated rehabilitation design and cost computation.

CHARACTERISTICS OF THE PILOT ROUTES

According to the pavement management system (PMS) of the Street and Bridge Division of the City of Austin, pavement conditions in Austin are evaluated and recorded by the following three indexes:

1) SDI — Surface Distress Index,
2) RCI — Riding Comfort Index, and
3) PQI — Pavement Quality Index.

These three indexes were originally developed by M. A. Karan and used as pavement performance model of PMS for the province of Alberta, Canada (Ref 47). In the original paper, SDI was called VCI (Visual Condition Index). The index was based on a scale of 0 to 100, then divided by 10 to make it compatible with RCI and PQI. Briefly, SDI represents the amount and severity of surface distress correlated with surface visual condition rating, climatic district indicator, and age. RCI is related to the roughness of the pavement and is highly influenced by the age of the pavement (Ref 47). Finally, the PQI is a combination of RCI, SDI and other factors. PQI represents the overall quality of the pavement condition. Each model can be used individually to predict performance for particular needs. All the indexes are on a scale of one to 10.

The worse a pavement condition is, the lower its index value. Minimum acceptable levels of the three indexes are as follows:

Indexes:	SDI	RCI	PQI
Maximum value	10	10	10
Minimum value	3.5	5.5	4.7
Allowable Drop	6.5	4.5	5.3

However, the pavement condition input required by the MPRDS-1 program for overlay design is not an SDI, RCI, or PQI value, but the remaining life (RL) of the pavement in percent. The AASHTO Design Guide of 1993, provides a formula to calculate the RL (Ref 33), which is

$$RL\ (\text{percent}) = 100\,[1 - (N_p / N_{1.5})]$$

where

N_p = total 18-kip ESAL to date,

$N_{1.5}$ = total 18-kip ESAL to pavement "failure" (P_2 = 1.5, the minimum acceptable level of PSI).

Unfortunately, we do not have (N_p, $N_{1.5}$) available for the old existing city streets. Therefore, we have to estimate the RL using known indexes. Since each of the indexes is a performance model, any of them can be used to estimate the RL. For example, if we favor the overall pavement quality, we may use PQI to estimate the RL by the following form

$$RL_{(estimate)} \text{ percent} = (PQI_{(to\ date)} - PQI_{min}) / (PQI_{max} - PQI_{min}) \times 100.$$

The result can then be modified by considering other indexes and the year when the pavement was last improved. We may also use SDI or RCI instead of PQI to estimate the RL. Staff of the Street and Bridge Division of the City of Austin[2] prefer to use SDI, the surface distress index, as the major factor to estimate the RL. For this study, a combination of these three indexes is used. First, RL is calculated from each of the three indexes using the above formula, then the three results of RL are combined by weighting coefficients, 0.6 for SDI, and 0.2 for both RCI and PQI. The year when the pavement was last improved is used for modification, and the number is rounded to the nearest five percent. The calculation is as follows:

$$RL_{(modified)} \text{ percent} = (RL_{(estimate)} \text{ percent of SDI}) \times 0.6 + (RL_{(estimate)} \text{ percent of RCI}) \times 0.2 + (RL_{(estimate)} \text{ percent of PQI}) \times 0.2.$$

The $RL_{(modified)}$ percent of pavements and other properties of the three pilot routes are shown in Tables 8.1, 8.2, and 8.3.

[2] Telephone interview with Mr. Vance Rodgers, engineer of the Street and Bridge Division of the City of Austin, May 26, 1994.

TABLE 8.1 PAVEMENT PROPERTIES OF IF BUS ROUTE

Sect. No.	Length (mile)	Width (ft)	Structure type	Number of lanes	SDI	RCI	PQI	Year improved	Modified RL (%)
1	0.21	27	2	2	5.17	6.11	5.3	1986	20%
2	0.308	37	2	2	8.69	8.69	8.4	1985	70%
3	0.308	27	1	2	7.11	4.73	4.4		30%
4	0.225	27	1	2	5.68	5.72	5.0		20%
5	0.438	37	2	2	6.51	6.11	5.5	1985	35%
6	0.2	37	2	2	6.51	6.11	5.5	1985	35%
7	0.19	37	2	2	7.67	7.84	7.4	1985	60%
8	0.225	37	2	2	7.67	7.84	7.4	1985	60%
9	0.131	37	2	2	7.67	7.84	7.4	1985	60%
10	0.078	37	2	2					20%
11	0.275	48	2	2	8.69	7.98	7.7	1985	70%
12	0.133	65	2	4	9.99	8.68	8.7	1993	95%
13	0.297	58	2	4	4.96	5.49	4.7		15%

TABLE 8.2 PAVEMENT PROPERTIES OF FW BUS ROUTE

Sect. No.	Length (mile)	Width (ft)	Structure type	Number of lanes	SDI	RCI	PQI	Year improved	Modified RL (%)
1	0.277	37	2	2	7.71	8.38	7.9		65%
2a	0.156	37	2	2	7.73	3.4	3.2		25%
2b	0.313	41	2	2	8.56	6.41	6.2		60%
3	0.213	41	2	2	7.74	5.61	5.3		40%
4	0.656	41	2	2	7.88	7.98	7.5	1987	65%
5	0.291	62	3	6	8.41	8.18	7.8	1988	70%
6a	0.257	41	3	4	9.14	5.86	5.7	1985	55%
6b	0.703	57	3	4	9.17	8.69	8.5	1985	80%
7	0.342	57	3	4	8.33	6.33	6.1	1982	50%
8	0.19	60	3	4	6.8	4.94	4.5	1988	30%
9	0.388	60	3	4	6.8	4.94	4.5	1988	30%
10	0.255	60	3	4	7.58	5.38	5.0	1988	40%
11	0.153	60	3	4	7.58	5.38	5.0	1988	40%
12	0.134	65	2	4	9.99	8.82	8.8	1993	95%
13	0.153	27	2	2					40%
14	0.134	50	2	2	4.97	6.11	5.2		20%

Note: Width, SDI, RCI, and PQI data are obtained from the data base of Street and Bridge Division of the City of Austin.

TABLE 8.3 PAVEMENT PROPERTIES OF #1 BUS ROUTE

Sect. No.	Length (mile)	Width (ft)	Structure type	Number of lanes	SDI	RCI	PQI	Year improved	Modified RL (%)
1	0.34	61	3	4	8.08	7.52	7.1	1984	60%
2	0.335	61	3	4	6.01	6.11	5.4	1984	30%
3a	0.089	68	3	6	9.01	7.03	6.9	1985	65%
3b	0.067	40	3	4	8.15	5.91	5.6	1985	45%
3c	0.067	46	3	4	8.66	5.91	5.7	1985	50%
4a	0.207	57	3	4	7.3	5.15	4.8	1984	30%
4b	0.138	47	3	4	7.37	3.93	3.7	1984	25%
5	0.23	37	3	2	6.92	4.52	4.1	1984	25%
6	0.345	57	3	4	7.57	4.52	4.2	1991	40%
7	0.23	57	3	4	6.38	4.94	4.4	1982	20%
8	0.108	57	3	4	5.86	3.4	3.0	1984	10%
9	0.737	60	3	4	7.58	5.38	5.0	1988	40%
10	0.255	60	3	4	7.35	5.86	5.4	1988	40%
11	0.58	60	3	4	6.8	4.94	4.5	1988	30%
12	0.625	60	3	4	8.12	7.98	7.6	1988	65%
13a	0.398	37	3	2	9.89	8.28	8.4	1985	85%
13b	0.74	60	3	4	8.60	7.84	7.6	1990	70%
14	0.93	60	3	4	8.41	8.18	7.8	1990	70%
15	0.808	60	3	4	8.41	8.28	7.9	1990	70%
16	1.4	60	3	4					50%
17	0.13	60	3	4					50%
18	0.3	41	2	4	7.75	6.41	6.0		50%
19	0.13	41	2	4	9.53	8.08	8.0	1988	80%
20	0.3	21	2	2	8.14	7.46	7.1	1986	60%

In these tables, width, SDI, RCI, PQI, and the year when the pavement was last improved are obtained from the data base of the Street and Bridge Division of the City of Austin. Data were last updated in August, 1993. In addition, section lengths were approximately measured from the 1992 Travis County traffic map. Number of lanes were obtained from observation.

STRUCTURAL PROPERTIES OF EXISTING PAVEMENT

According to the Street and Bridge Division of the City of Austin, street pavements in Austin generally have two layers: a surface layer of dense asphalt concrete and base layer of bituminous stabilized granular materials (Ref 46) (Fig 8.1).

Subgrade soil condition varies in the city. Surface soil is usually lime treated for improvement but is not considered a layer. Pavement structures for different street categories can be categorized into three types, which basically fit different traffic values. Street pavements in Austin were not as strongly built as highways in rural areas, therefore, they are easily damaged by heavy bus axle loads.

Pavement structure Layers	Type 1 (Residential Street)	Type 2 (Collector Street)	Type 3 (Arterial Street)
Surface	1.5"	2.5"	3.0"
Base	8.0"	10.0"	12.0"
Subgrade Soil	---	---	---

Fig 8.1 General structure of street pavement in the City of Austin

In order to simplify data inputs in overlay design procedure, Types 1 and 2 can be modified to have the same surface thickness as Type 3 while keeping approximately equal structure number (SN). The simplified structure types for overlay design inputs are as follows:

Thickness of	Type 1	Type 2	Type 3
Surface layer	3.00"	3.00"	3.00"
Base layer	6.00"	10.00"	12.00"

Structure types of sections of the three pilot routes are shown in Tables 8.1, 8.2, and 8.3. Elastic moduli (resilient moduli) used in pavement design exist in a wide range. Since field test data are not available, this variable and Poisson's ratio are assumed. Referring to the AASHTO Design Guide of 1993, the following assumptions for layer material properties are made:

LAYER	DESCRIPTION	E-MODULUS	POISSONS RATIO
1	Asphalt Concrete	450000 psi	0.30
2	Bituminous Stab.	100000 psi	0.35
Subgrade	Clayey Gravel	10000 psi	0.40

Percent reliability is another parameter for overlay design which is based on the importance of the streets and the traffic level. For arterial streets this value is taken between 80 and 95 percent, and for collector streets between 75 and 85 percent.

TRAFFIC PARAMETERS

Traffic parameters, such as ADT, the percent heavy trucks in the ADT, ESALs, traffic growth rate, and traffic distribution factors are important inputs for pavement design. In this study, these parameters are paired in two batches of data representing the two different fueled bus operations. One group of data is for the normal traffic using diesel buses on bus routes, and the other is for the same traffic but using CNG buses.

Since most of the ESALs applied on street pavements are attributed to heavy trucks and buses, the traffic growth rate should be determined based on these two vehicle categories. From the previous analysis in Chapter 6, we can assume one percent for vehicle growth rate in the Austin area.

To simplify traffic load input data, buses and trucks were combined as a single vehicle item (trucks+buses), and then its percentage in the ADT was calculated. This is an important simplifying step for load inputs. Following is an example, if percent trucks in ADT is one percent for a road section, then the percent (trucks + buses) in the ADT is calculated as

Percent (trucks+buses) = [ADT x 50 percent x 1 percent + (number of daily bus repetitions)] / (ADT x 50 percent)

where the number 50 percent is the directional distribution factor. As mentioned in Chapter 7, the lane distribution factor of (trucks+buses) for the side lane can be taken as 100 percent.

The ESAL per unit of (trucks+buses), or the average ESAL factor can be obtained through the following computation (applications in a 24-hour weekday on design lane):

ESAL per unit of (trucks+buses) = [(Total ESAL of trucks) + (Total ESAL of buses)] / (Total trucks + Total buses).

The ESAL value for an average city truck can be estimated between 0.4 to 0.8 (Ref 44).

Percent (trucks+buses) in ADT and average ESAL factor of (trucks + buses) for the three pilot routes are shown in Appendix 5.

UNIT COST OF OVERLAY REHABILITATION

According to the AASHTO Design Guide of 1993 (Ref 33), pavement maintenance & rehabilitation (M&R) methods fall into two categories, M&R with and without overlay. Since overlay is a common rehabilitation method, we use overlay as the pavement rehabilitation option to analyze the cost impact under diesel bus operations and CNG bus operations in the bus route system. In order to determine unit costs as one of the common parameters in a cost analysis, the items that are related to overlay construction and generate costs should be generalized. Based on several bid tabulations prepared by the City of Austin, Department of Public Works and Transportation (Ref 48), the items are as follows:

1) Crack sealing,
2) Seal coat,
3) Edge and surface milling of asphalt concrete pavement,
4) Hot mix asphalt concrete pavement overlay,
5) Concrete curb and gutter construction,
6) Triangular sediment filter dikes with sand bags,
7) Barricades, signs and traffic handling,
8) PVC ducts, and
9) Thermoplastic pavement markings.

Among these items, hot mix asphalt concrete pavement overlay is the major construction item. Cost of this item is a variable because it varies with change of the thickness of the overlay in different design alternatives. The cost of this item can be calculated as the thickness of the overlay multiplied by the unit cost per cubic yard of the overlay hot mix AC. In the MPRDS-1 program this is called the Unit Construction Cost ($/CY).

The cost for the rest of the items can be considered fixed, because for a certain section of road these items can be kept constant while the pavement overlay thickness is changed. The total cost of these items divided by the total area of the section is the unit price that in the MPRDS-1 program is called the Fixed Construction Cost ($/SY). This fixed cost is used along with the Unit Construction Cost ($/CY) to predict the total placement cost.

The third cost used in analysis is the Site Establishment Cost ($), which is a fixed cost for a certain M/R project for mobilizing manpower and equipment for construction of the overlay. This cost term can be assumed to be five percent of the total bid price of an overlay project.

The following is the determination of the three cost parameters. Unit prices used in this study are based on 1993 bid prices of rehabilitation projects in the City of Austin.

The Fixed Construction Cost ($/SY).

This cost is related only to the overlay M/R method. It can be obtained from bid prices of overlay projects.

Bidder	Project: Windsor Rd. 24th Overlay	Project: First St. Overlay
NBS Construction Inc. (Austin, TX)	$9.32 /SY	------
Austin Bridge & Road (Austin, TX)	$6.42 /SY	$2.39 /SY
Pool and Rogers Paving Co. (Buda, TX)	$8.26 /SY	$3.07 /SY
Metro Paving Co. (Del Valle, TX)	$15.57 /SY	------

Source: Ref 48

Ignoring the most extreme numbers, the average bid price is (6.42+2.39+ 8.26+3.07)/4 = $5.0/SY, which gives an estimate of the Fixed Construction Cost.

The Unit Construction Cost ($/CY).

This unit price is the dollars per cubic yard of the overlay hot mix AC. To get this unit cost, we take a total cost of hot mix asphalt concrete from the Bid Tabulations and divide it by the number of square-yards of the area being paved and by the thickness of the asphalt concrete. Results of the calculation are as follows:

Projects	Bidders (1)	Bidders (2)	Bidders (3)	Bidders (4)
Windsor Rd. 24th overlay	81	72	92	126
1st St. overlay (Mopac-IH-35)	--	58	75	___
Oltorf rehab	77	62	72	___
Riverside Dr. rehab (Lamar-1st)	--	99	98	114
'92 CMTA bus RDWY GRP 3 IMPR 26th & Oltorf	--	63	72	___
Springdale Rd rehab (E 12th-Rogge Ln)	_	59	72	___
CMRA '92 roadway improve. (E. 6th & W. 29th)	_	72	74	___

Source: Ref 48.
Bidders: (1) NBS construction INC., (2) Austin Bridge & Road, (3) Pool and Roge Paving Co. (Buda, TX), and (4) Metro Paving Co. (Del Valle, TX).

Unit costs from bidders (2) and (3) are used to calculate the mean and standard deviation of these unit prices. The mean is $74/CY. The standard deviation is $13.3/CY. The mean gives the best estimate of the Unit Construction Cost ($/CY).

The Site Establishment Cost ($)

Since the size of the projects is variable, this cost is relatively difficult to determine. We use a one mile length of road as an unit and then divide the five percent of total cost by the length of the road. Taking the First Street overlay project (from Mopac to IH 35) to calculate the value:

Bidder: Austin Bridge and Road.
Length of the road: 2.172 miles.
Total bid price: $ 413,677.20.
(413677.20 x 5 %)/2.172 = $9523.

This number is rounded to $10,000, which gives the estimation of site establishment cost ($) for a one-mile length of the site.

COMPUTER PROGRAM USED IN THE REHABILITATION COST ANALYSIS

The computer program used to obtain the rehabilitation cost in this study is MPRDS-1. It was developed by ARE Engineering Consultants, Austin, Texas for the Houston Metropolitan Transit Authority (METRO). As the author stated in the "User's Manual:"

> "The MPRDS-1 program itself was adapted from versions of a rehabilitation design program that was developed initially for the Texas SDHPT and later for Pennsylvania DOT. The additional features incorporated, based on experience in the City of Austin, permit an agency to consider many of the factors associated with municipal street design and construction within a life-cycle cost analysis framework" (Ref 44).

Rehabilitation cost in this program calculates not only the overlay construction costs, but also the user delay cost due to construction work of rehabilitation. A maximum of four layers can be considered in the program. The layer thickness in this program has limitations, in that thickness for both existing layers and overlay cannot be less than three inches. Thus, sections with very low traffic load have to take a three inch overlay that may give disproportionately high cost outputs. A maximum of eight different alternative thicknesses are allowed in the program. This program may generate as many as eight design alternatives. In order to carry out a reasonable comparison study, we select a pair of reasonable design alternatives from outputs for diesel bus operations and CNG bus operations.

All cost outputs of MPRDS-1 are unit costs in terms of dollars per square yard ($/SY) which have been brought by the program to net present value from the time the design strategy is expected to last. Cost outputs consist of the following items:

1) overlay construction cost ($/SY) (of first layer and second layer),
2) overlay traffic delay cost ($/SY),
3) overlay maintenance cost ($/SY),
4) value of extended life ($/SY),
5) overlay salvage value ($/SY),
6) total net present value of the overlay design strategy ($/SY).

Item (6) is the final cost of the overlay rehabilitation calculated by the following procedure:

(6) = (a)+ (b) + (c) - (d) - (e), ($/SY).

By using this program, it was found that sections with very high remaining life, RL (percent), may get strange design alternatives and costs, which may be because the section is too new to be considered for rehabilitation. Overall, this program is simple, user-friendly, and self explanatory.

EVALUATION OF THE IMPACT ON PAVEMENT REHABILITATION COSTS (1)—PILOT ROUTE STUDY

As mentioned at the beginning of this chapter, the impact of CNG bus operations on street pavement rehabilitation cost (R-Cost) is estimated by percent cost increase in a 20-year design period.

For one pavement section, the percent cost increase of the rehabilitation, or the cost increment, is simply calculated by the following expression:

Cost Increment (percent) =

[(R-Cost under CNG bus operations) - (R-Cost under diesel bus operations)] / (R-Cost under CNG bus operations)] x 100 percent.

For an entire bus route the cost increment under CNG fuel bus operations is measured by average cost increment weighted by the areas of sections in the route. Since sections are not equal in length and width, cost increment cannot be simply averaged.

Three pilot bus routes, each with more than 10 independent sections, were processed by the MPRDS-1 program. Results for each bus route are summarized below.

Study Results of IF Bus Route

Results are shown in Table 8.4 and Figure 8.2.

The impact of CNG bus operations on street pavement rehabilitation cost in a 20-year design period are estimated as follows:

1) The average weighted cost increment (percent) = 6.2 percent,
2) The average weighted cost increment ($/SY) = $1.4/SY,
3) The range of cost increment (percent) is 2.1 to 13.4 percent.

TABLE 8.4 REHABILITATION (OVERLAY) COSTS COMPARISON FOR IF BUS ROUTE

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

*For 20-year design period
**Section 12 on 26th Street is excluded from these calculations because it was reconstructed in 1993.

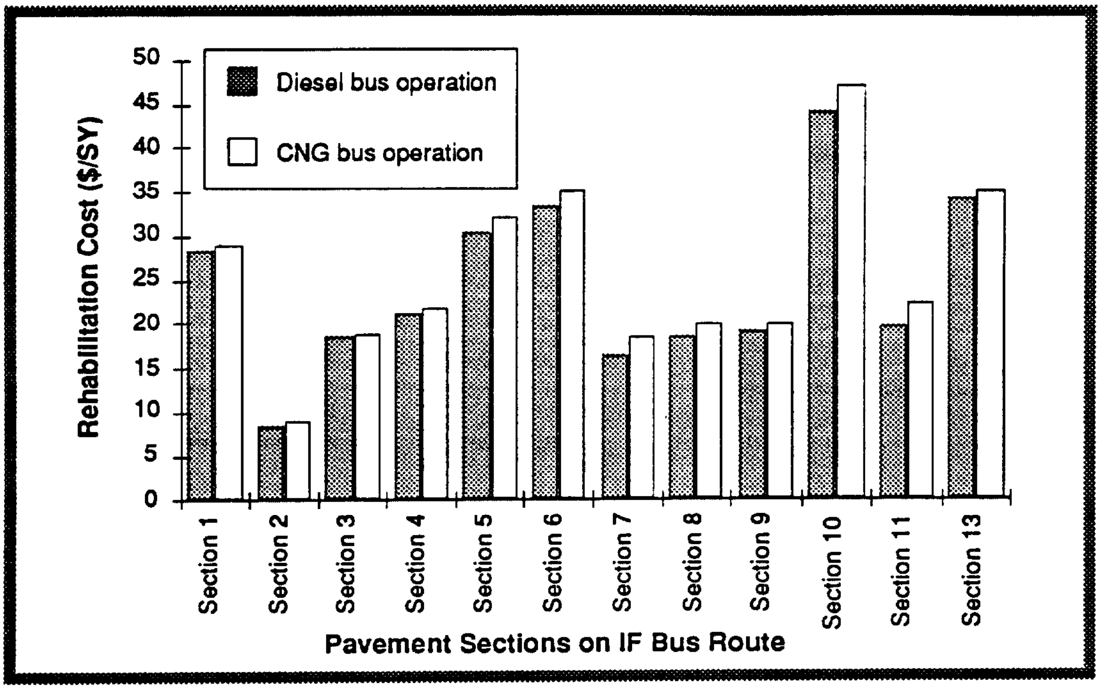


Fig 8.2 Rehabilitation unit cost comparison in each section of IF Bus Route

Study Results of FW Bus Route

Results are shown in Table 8.5 and Figure 8.3. The impact of CNG bus operations on street pavement rehabilitation costs in a 20-year design period are estimated as follows:

1) The average weighted cost increment (percent) = 7.1 percent.
2) The average weighted cost increment ($/SY) = $1.1/SY.
3) The range of cost increment (percent) is 1.8 to 17.1 percent.

TABLE 8.5 REHABILITATION (OVERLAY) COSTS COMPARISON FOR FW BUS ROUTE

Section Number	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	1399000	1455000	4.0%	3.82	4.36	14.1%
2a	1394000	1451000	4.1%	15.44	15.99	3.6%
2b	1394000	1451000	4.1%	5.54	6.07	9.6%
3	1633000	1779000	8.9%	13.36	14.67	9.8%
4	1657000	1804000	8.9%	6.97	8.16	17.1%
5	2415000	2480000	2.7%	13.43	13.77	2.5%
6a	3327000	3610000	8.5%	22.94	24.42	6.5%

TABLE 8.5 REHABILITATION (OVERLAY) COSTS COMPARISON FOR FW BUS ROUTE
(Continued)

Section Number	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 %
6b	3327000	3610000	8.5%	20.58	21.92	6.5%
7	2793000	2991000	7.1%	16.93	17.78	5.0%
8	4087000	4345000	6.3%	30.11	31.04	3.1%
9	4333000	4672000	7.8%	37.17	39.22	5.5%
10	4350000	4692000	7.9%	37.32	38.55	3.3%
11	4694000	5037000	7.3%	38.6	40.27	4.3%
13	1532000	1594000	4.0%	12.1	12.68	4.8%
14	1532000	1594000	4.0%	27.71	28.22	1.8%

*For 20-year design period
**Section 12 on 26th Street is excluded from these calculations because it was reconstructed in 1993.

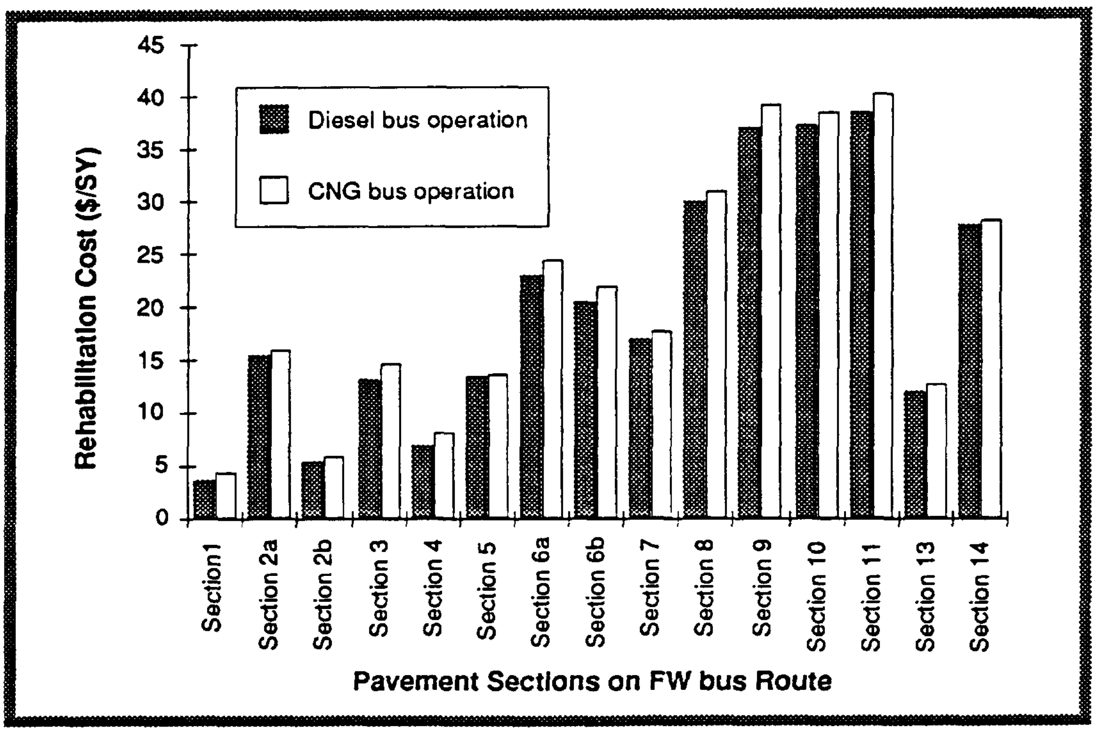


Fig 8.3 Rehabilitation unit cost comparison in each section of FW Bus Route

Study Results of #1 Bus Route

Results are shown in Table 8.6 and Figure 8.4. The impact of CNG bus applications on street pavement rehabilitation costs in a 20-year design period are evaluated as follows:

1) The Average cost increment (percent) weighted = 5.0 percent.
2) The Average cost increment weighted ($/SY) = $1.3/SY.
3) The Range of cost increment (percent) is 0.0 to 18.6 percent.

TABLE 8.6 REHABILITATION (OVERLAY) COST COMPARISON FOR #1 BUS ROUTE

Section Number	Cumulated ESALW/Diesel bus application	Cumulated ESALW/CNG bus application	ESAL Increase %	Cost ($/SY) under Diesel bus application	Cost ($/SY) under CNG bus application	Cost Increase %
1	4351000	5629000	29.4%	22.83	26.39	15.6%
2	3334000	4320000	29.6%	23.57	26.59	12.8%
3a	5914000	6725000	13.7%	25.30	26.74	5.7%
3b	5914000	6725000	13.7%	24.86	25.67	3.3%
3c	5914000	6725000	13.7%	29.56	30.94	4.7%
4a	3517000	3904000	11.0%	26.63	27.95	5.0%
4b	3517000	3904000	11.0%	26.91	29.30	8.9%
5	2527000	3402000	34.6%	29.05	34.46	18.6%
6	3811000	4842000	27.1%	25.39	28.36	11.7%
7	2883000	3845000	33.4%	27.18	31.16	14.6%
8	3173000	4047000	27.5%	31.13	33.09	6.3%
9	6126000	7022000	14.6%	39.35	42.71	8.5%
10	4331000	4560000	5.3%	35.82	37.76	5.4%
11	4312000	4542000	5.3%	37.00	38.51	4.1%
12	1956000	2011000	2.8%	15.97	16.69	4.5%
13a	2225000	2280000	2.5%	12.10	12.49	3.2%
13b	2225000	2280000	2.5%	17.19	17.58	2.3%
14	2449000	2500000	2.1%	18.87	19.20	1.7%
15	3164000	3215000	1.6%	24.11	24.11	0.0%
16*	2452000	2575000	5.0%	22.30	22.82	2.3%
17*	2246000	2290000	2.0%	20.97	21.12	0.7%
18	1446000	1490000	3.0%	14.48	14.48	0.0%
19	1375000	1420000	3.3%	13.48	13.53	0.4%
20	2016000	2155000	6.9%	20.89	21.02	0.6%

*For 20-year design period

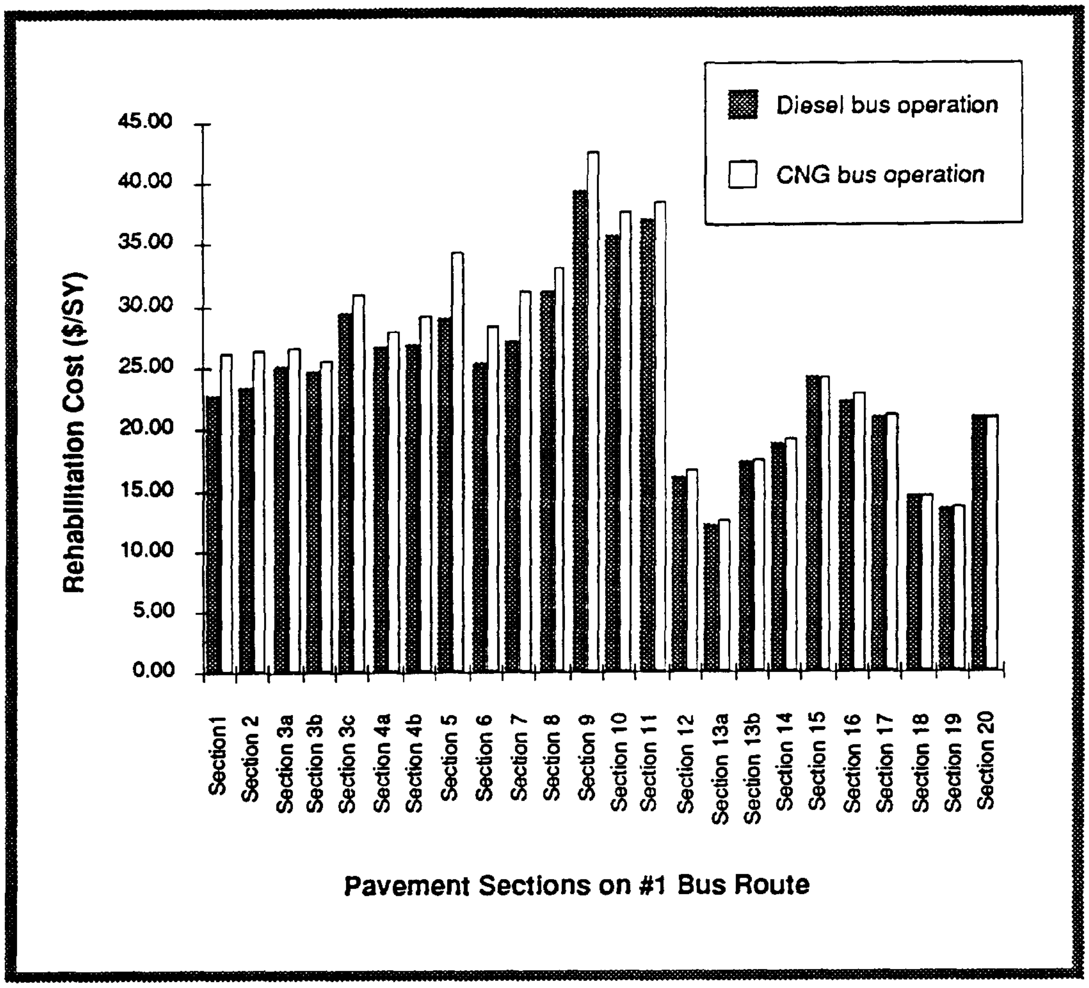


Fig 8.4 Rehabilitation unit cost comparison in each section of #1 Bus Route

EVALUATION OF THE IMPACT ON PAVEMENT REHABILITATION COSTS (2)—AN ESTIMATION MODEL

Each pavement section in the study is unique in location and is independent in overlay design. A total of 45 independent sections were involved in the study as a sample population of sections in the whole bus route system. Using the SAS computer program to analyze the sample of sections, a regression formula for estimating the increase in rehabilitation cost was obtained.

Rehabilitation cost depends on many factors, such as section length, width, pavement structure, cumulative ESALs, design period, traffic load level, and remaining life (RL). Some factors may have very little influence. In order to use the SAS program efficiently for obtaining an impact estimation model, we summarize these factors as eight variables:

1) ID - Section identification number;
2) LENGTH - Section length (mile);
3) WIDTH - Section width (ft);
4) STRUCT - Structure type of the pavement in the section;
5) RL - Remaining life of the pavement in the section, in percent value;
6) ESALEVEL - The cumulative ESALs of conventional diesel bus operations in the section for a 20-year design period (millions);
7) ESALINCR - Percent increase of ESAL due to CNG bus operations;
8) COSTINCR - Percent increase of the overlay rehabilitation cost due to CNG bus operations for 20-year design period.

The variable (8) is the only dependent variable in the analysis.

Simple statistical results on these data are as follows:

1) For variable RL (pavement remaining life, percent)
   The mean of RL = 45.2 percent,
   Standard deviation = 19.8 percent.
2) For variable ESALINCR (percent increase of the ESAL due to CNG bus operations, percent)
   The mean of ESALINCR = 9.6 percent,
   Standard deviation = 8.9 percent.
3) For variable COSTINCR (percent increase of overlay rehabilitation cost due to CNG bus operations)
   The mean of COSTINCR = 5.8 percent,
   Standard deviation = 4.3 percent.

From a SAS correlation analysis, it was found that variable COSTINCR is significantly correlated with ESALINCR. The correlation coefficient of the two variables is 0.81030, which is significant (P-value = 0.0001 << a = 0.05). Correlation coefficients between COSTINCR and the rest of the variables are very low and not significant.

From a multiple regression analysis using the SAS GLM (general linear model) procedure, in which all variables were taken into account, we found that the variables LENGTH, WIDTH, and ESALEVEL were not significant in contribution to the COSTINCR variance. The variable STRUCT seems to have a slight influence on the variable COSTINCR. In order to find an efficient and simple regression formula, we ignored the three insignificant variables from the first multiple regression process but kept ESALINCR, RL, and STRUCT in the multiple regression procedure. The final model is expressed as

$$\begin{aligned} &\text{COSTINCR (Rehabilitation cost increase, percent)} = \\ &= 3.2598 + 0.4595 \times (\text{ESALINCR}) + 0.0444 \times (\text{RL}) \\ &\quad - 1.5177 \times (\text{STRUCT}). \text{ (percent)} \end{aligned}$$

Where

STRUCT — Pavement structure type = 1, or 2, or 3 only. In this study there are only 3 basic types of pavement structure,

RL — Remaining life in percent,

ESALINCR — Percent increase of ESAL applications in the section, which is calculated by the following procedure including truck ESALs in the design lane,

ESALINCR = [(Total ESAL under CNG bus operations - Total ESAL under diesel bus operations)/(Total ESAL under diesel bus operations)] x 100 percent.

This is the regression model for estimating the impact of CNG bus uses on street pavements in a 20-year design period.

Below is an example showing how the regression model is used. For section 9 of #1 bus route, remaining life: RL = 40 (percent), ESAL increase: ESALINCR = 14.6 (percent), and structure type: STRUCT = 3. Then, the percent increase of overlay rehabilitation cost is

$$\begin{aligned} &\text{COSTINCR (Rehabilitation cost increase, percent)} \\ &= 3.2598 + 0.4595 \times (\text{ESALINCR}) + 0.0444 \times (\text{RL}) - 1.5177 \times (\text{STRUCT}). \text{ (percent)} \\ &= 3.2598 + 0.4595 \times 14.6 + 0.0444 \times 40 - 1.5177 \times 3 \\ &= 7.2 \text{ percent,} \end{aligned}$$

which is close to the originally calculated percent increase of rehabilitation cost of 8.5 percent.

Results of this study show that in most cases the rehabilitation cost increase (in percent value) is less than the ESAL increase (also in percent value). If remaining life, RL, and structure type, STRUCT, are kept constant, the slope of the linear regression line for cost increase, COSTINCR, can be expressed as

$$\partial\,(\text{COSTINCR}) / \partial\,(\text{ESALINCR}) = 0.4595.$$

This indicates that the increment of cost increase is proportionally less than the increment of ESAL increase by the ratio of 0.4595.

Also from the regression analysis, it can be shown that Type 3 pavement structure behavior is better than Type 2 and Type 1 in terms of increment of the percent increase of rehabilitation cost. This indicates that strong pavements have the potential ability to carry more traffic load, thereby reducing the cost increase for CNG bus operations. It should be pointed out that the high percent increase of rehabilitation cost does not necessarily mean a high monetary value, since the percentage is a relative value.

While the pilot-route studies have provided specific references for urban transportation planners to consider the impact on rehabilitation cost due to load increase under CNG bus operation, the regression formula enables engineers to estimate the impact on rehabilitation cost for any pavement section under CNG bus operation. This formula can also be used as an impact estimation model for other ESAL increase cases if the conditions are the same as in this study.

ESTIMATION CHARTS

Using the regression model, new charts can be produced for estimation of the percent increase rehabilitation cost. These charts were developed based on the MPRDS-1 overlay design program. The range of percent increase of ESALs is from two to 40 percent. The remaining life RL is assumed as 20, 30, 40, and 50 percent for four charts, respectively. The structure type is used as 1, 2, and 3 as they have been explained in the regression model. These charts are shown in Figures 8.5 and 8.6.

To use these charts, first compute the ESAL percent increase, then on the horizontal axis find the calculated ESAL increase, then from the solid line representing the structure type find the corresponding Y value. This is the estimation of the percent increase of overlay cost. The charts may also be used for other ESAL increase cases.

At the end of this chapter, mathematical equations are presented to address the objectives of this study. It is now necessary to synthesize results of previous chapters and to develop the final conclusions. This is the focus of the next chapter.

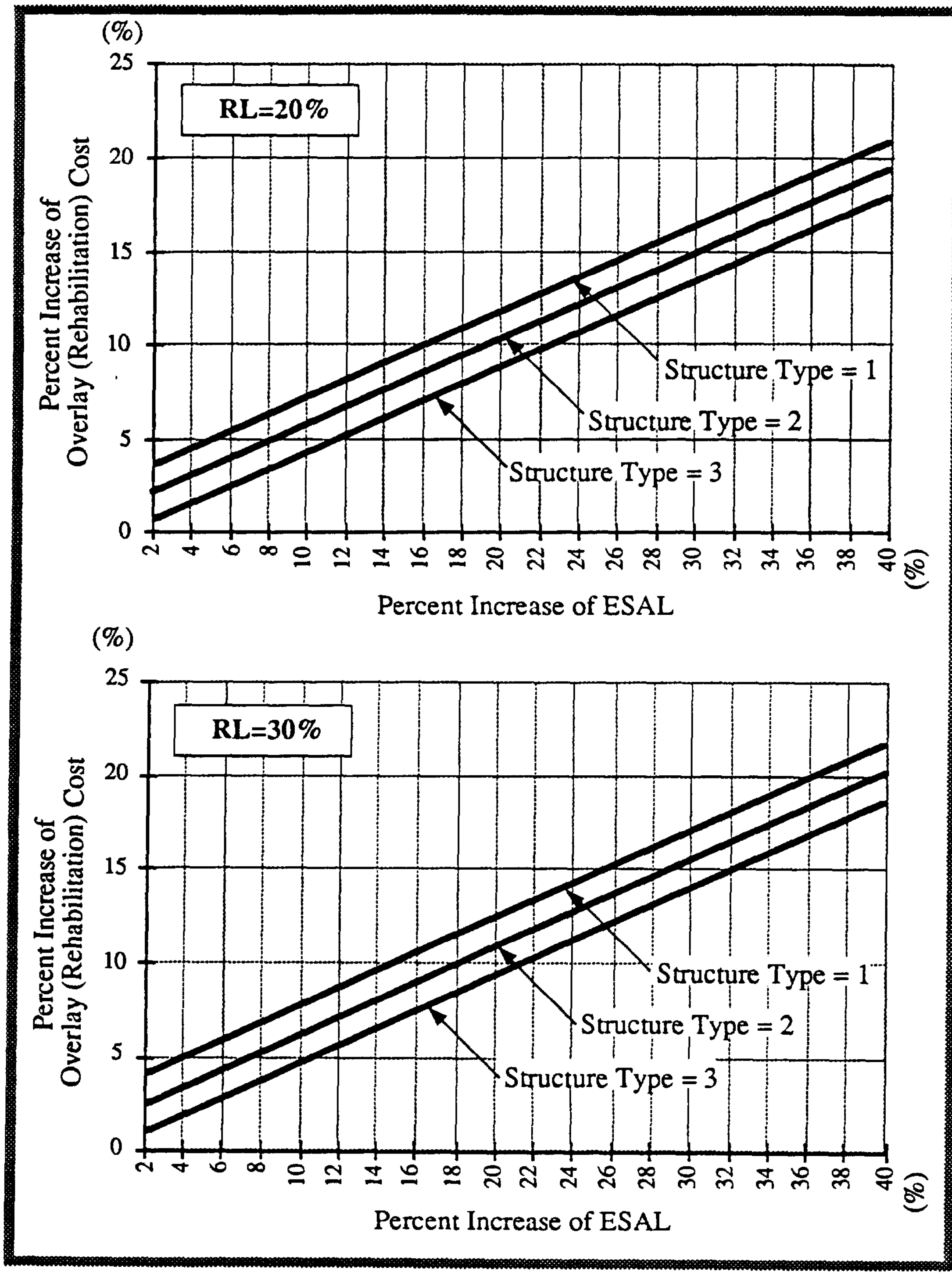


Fig 8.5 Charts for estimating R-costs increase (1) (for 20-year design period)

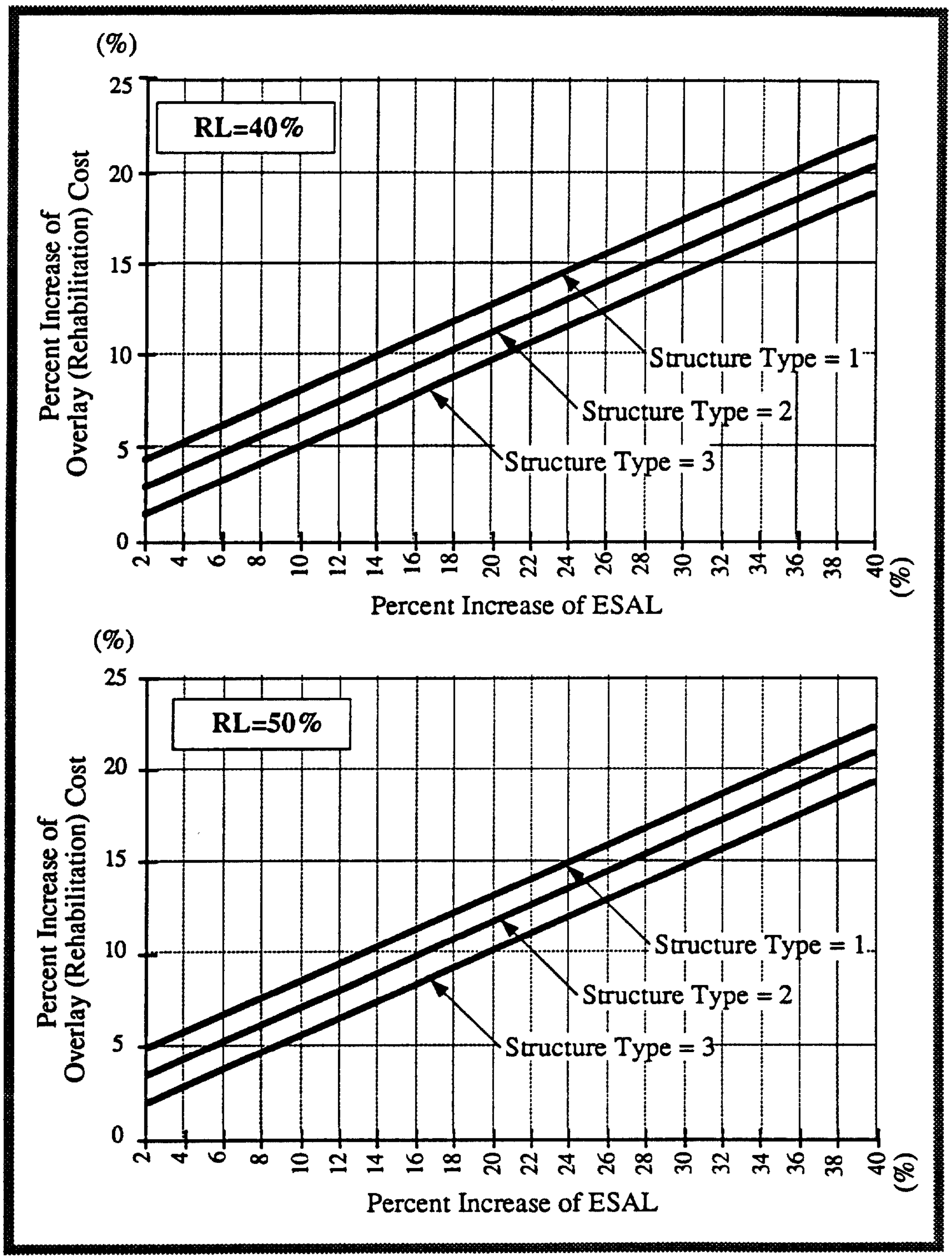


Fig 8.6 Charts for estimating R-costs increase (2) (20-year design period)

CHAPTER 9. DISCUSSION OF RESULTS

In Chapters 1 through 8, solutions for the major aspects of this study, evaluating the impact of CNG bus operation on street pavement, have been presented. The percent increase of number of ESALs on pavements have been calculated, and the percent increase of pavement rehabilitation cost is evaluated. Since this study involves a wide range of social, technical, and engineering issues, it is necessary now to synthesize and discuss the preceding findings and draw some conclusions. The following section presents a discussion on results.

CNG FUEL TANKAGE

As shown in the previous chapters, the matter of fuel tankage is the crux of the problem. In order to perform as well as a diesel fueled vehicle, a CNG fueled vehicle carries extra weight due to the pressurized tanks needed to store CNG fuel. This additional weight in turn affects vehicle performance and increases consumption of street pavements.

This study suggests that a factor of 17 lbs be used to estimate the extra weight for each equivalent gasoline gallon of CNG fuel carried. It should be pointed out, however, that this number is based on using composite-reinforced aluminum cylinders for CNG tanks only. If steel cylinders are employed, this number should be increased due to the greater weight of the steel. For example, if each additional seat increases bus weight by 235 lbs,[3] then a TMC CNG bus with 47 seats would weigh 30,260 lbs. Thus, under the same seating capacity, the curb weight of a TMC CNG bus would be 2,000 lbs greater than that of a GILLIG 1100 diesel bus. On the other hand, using the 17 lbs to estimate the weight increase, a GILLIG 1100's CNG counterpart would carry extra weight of 2,040 lbs (with 120 equivalent gasoline gallon capacity), which is close to 2,000 lbs.

Weight increase is a real concern to transit authorities. A report from Houston METRO noted the following:

> "The weight of the CNG tankage required to provide a 350-mile range would severely reduce the peak hour standing load opportunity utilized by all METRO

[3] This can be obtained by comparing GILLIG 1100 (47 seats) with GILLIG 1700. Since the only difference between these two is the length of wheelbase (WB) regarding seating capacity, for each additional seat the weight increase would be

(28,260 (curb weight of GILLIG 1100) - 26,380 (curb weight of GILLIG 1700))/8 = 235 lbs.

transit systems, as well as requiring significant vehicle structure and component changes" (Ref 49).

Thus, the METRO's choice of fuel is LNG (Ref 49). DART has also selected LNG, possibly for the same reason.

Increased weight due to fuel storage requirements is the main drawback to CNG conversion. This problem will undoubtedly be alleviated in the future with the development of CNG fuel uses, production of lighter weight cylinder tanks, and improvements in the CNG refueling system. Of course, using LNG is one way to solve the problem today. Consequently, the choice of fuel is a strategic decision which should be made based on results of a long term comprehensive study on the use of clean alternative fuels.

PASSENGER LOADING

Results of this study strongly indicate the necessity and importance of choosing passenger occupancy levels when determining bus ESALs. Using the GILLIG 1100 bus, for example, if occupancy is based on 20 passengers rather than 15 passengers, the five-passenger difference contributes to a 10 percent increase in the bus ESALs. If we consider that buses contribute 85 percent of total ESALs on a bus route, this increase will be as much as 8.5 percent of the total ESALs of the route. Obviously, this is a significant change. Thus, it is important to choose reasonable passenger occupancy levels before calculating ESALs since buses are the major loading source to street pavements and these loads are very sensitive to passenger occupancy.

It is not, however, difficult to determine passenger occupancies for each section of a specific bus route. As studied in Chapter 4, for an established fixed bus route, a trend pattern of passenger occupancy along this route can certainly be found, and based on this pattern, the passenger occupancy level for each route section can be determined. This may not be possible for a newly established route, as passengers are not yet familiar with it, and there is uncertainty with the pattern. In order to simplify this matter, sections related to passenger occupancy can be classified into five levels, very dense, dense, medium, low and very low.

Generally, the numbers of passengers for a standard bus is from zero to 75. Although the maximum number of passengers may reach 77 (an example of the IF bus route at the corner of Speedway and Grooms, based on a survey conducted by Capital Metro in 1992) the average passenger occupancy for dense bus routes in Austin is usually around 20 or 25. Most of the time, the passenger occupancy is one-third to one-half of the seating capacity, except during peak hours. On average, we can assign a number from five to 25 as the level of passenger occupancy for the five-level route sections in Austin.

TRAFFIC LOADING CONDITIONS ON STREET PAVEMENT

This study has reflected that traffic loading on bus routes is much heavier than on other streets, since buses contribute a very high percentage of ESALs in total compared to other vehicles on streets of bus routes. This argument can be verified by pilot route studies. On average, buses account for 76 percent of the ESALs applied to the sections of the #1 route. These numbers for the FW bus route and the IF bus route are 87 and 96 percent, respectively. ESALs of a bus route may be as high as five times that of ESALs on streets without bus lines. In absolute terms, this is significant and suggests that pavements on bus routes should be treated differently by the pavement management system in the city.

ESALs on bus routes are also higher than those on some freeways. This difference can be illustrated by using the #1 bus route as an example. The maximum number of ESALs in section 9 of this route, Guadalupe St. from MLK to 27th St., is 762. In comparison, the ADT value recorded at count station MS-209 on Loop 1 in 1992 was 104,925. The ESALs at this section of Loop 1 were calculated at 367 [4], significantly lower than 762, as well as the ESALs on sections 1, 2, 3, 4, 6, 10, 11, and 15 of the #1 bus route. This comparison further indicates the necessity of different treatment to the pavement on bus routes.

Recently, the Texas Department of Transportation has contemplated a new philosophy with the possibility of increasing funds to improve city streets (Ref 50). This is good news to city pavement engineers, of course, but it should be emphasized that bus route pavements deserve even more attention.

EVALUATION OF THE IMPACT ON PAVEMENT PERFORMANCE

Among these pilot routes, IF and #1 are the most dense bus lines in both the UT shuttle bus and Capital Metro bus systems. The FW bus route is less dense than the IF route but is still a busy line in the shuttle bus system. These three routes were chosen for the pilot study because of their importance in the city of Austin and the high likelihood of operating CNG fueled buses.

The impact of using CNG buses instead of diesel buses on pavements has been evaluated based on the pilot route study. Results are shown in Chapter 7. It should be pointed

[4] Assume average equivalent 18-kip single axle load factor for trucks on freeway of flexible pavement is 1.0 (Ref 44), lane distribution factor is 70 percent, heavy trucks in ADT of Loop 1 is 1.0 percent, and directional distribution factor is 50 percent. Then, ESALs of the design lane of the Loop 1 is

104,925 x 50 percent x 70 percent x 1.0 percent x 1.0 = 367.

out that sections with a high percent increase of ESALs are those sections in which GILLIG 1700 and/or GILLIG 1600, or Dillo diesel buses are operated. These three buses are much lighter than TMC CNG buses because of the light diesel fuel tankage and the lower seating capacities. The ESAL factors of these three types are 20, 25, and even 80 percent less than the TMC CNG bus. Conversely, the TMC CNG bus has a smaller seating capacity than the GILLIG 1100 or GILLIG 1000, thus the expected impact will be reduced if the TMC CNG bus is used instead of GILLIG 1100. In reality, since Capital Metro is unlikely to increase or decrease buses on a route to offset the difference of seating capacity, adjustments for the difference of seating capacity have not been used in this comparison study. In the future, however, if Capital Metro uses relatively small CNG buses which are compatible with GILLIG 1700, GILLIG 1600, or Dillo buses, the percent increase of ESALs due to CNG bus operation will certainly be reduced.

In addition, a high value of the percent increase of ESALs in some route sections do not necessarily mean a high increment of the ESALs because the percentage is a relative value. This is especially true for sections with a small number of bus repetitions. For instance, two sections on the PRC bus route have small ESAL increments even though the percentages of increase of ESALs are very high.

Chapter 7 shows that the increase of ESALs under CNG bus operation is about 6.7 percent for the entire Capital Metro bus route system. This result is due to buses alone. If truck ESALs are counted in this analysis, the 6.7 percent will decrease. Pilot studies in Chapter 8 show that, on average, buses and trucks contribute 85 percent and 15 percent of the total ESALs on bus routes, respectively. Considering that trucks produce 15 percent of the total ESALs in the entire route system and CNG buses produce 85 percent, the estimation of ESAL increase for the entire route system under CNG bus applications will change to (85 percent x 106.7 percent + 15 percent) - 100 percent = 5.7 percent. From this calculation, the ESAL increase may be estimated as five to six percent for the entire route system.

All impact estimations in this study are based on the situation that truck traffic is less than one percent in ADT. For bus routes with a high percentage of truck traffic in the ADT volume, the impact of CNG buses will be less severe. For instance, a route in the previous study has six percent increase of ESALs due to the use of CNG buses, and buses and trucks contribute 85 percent and 15 percent of the total ESALs, respectively. If the percentage of trucks in ADT increases from one to three percent, which is three times the original 1.0 percent, then the percent increase of ESALs will decrease to four percent [5]. The impact as the ESAL increment is considerably reduced.

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[5] This estimation can be obtained by the following calculation:

The #1 route in particular has high passenger occupancy and number of bus lines. Thus, some sections of the #1 route have a very large ESAL increment, as high as 34.5 percent with the use of CNG buses. However, this high increment is partly due to the replacement of the much lighter Dillo buses with TMC CNG buses. For the majority of bus routes, six percent seems a reasonable value to estimate the increase of pavement damage under CNG buses.

EVALUATION OF THE IMPACT ON COST OF PAVEMENT REHABILITATION

Although the three pilot routes are only a small portion of the entire Capital Metro route system, they represent a cross section of the characteristics of the entire system. In this study, each section of a route is an independent overlay design case, unique in location and condition. Estimation of these three pilot routes can be used as valuable references to estimate other routes. For the entire bus route system in Austin, if the average remaining life (RL) is estimated to be 45 percent and the ESAL increase is five percent, structure type 2, then for a 20-year design period the overlay rehabilitation cost increase under CNG fueled bus application would be four to five percent.

In addition, the design period has no influence on the percent increase rehabilitation cost. Several sections with remaining life of 30 to 40 percent have been selected for confirmation under 15-, 20-, 25-, and 30-year design periods. The following are the collected results.

Section ID	RL (%)	15 Yr	20 Yr	25 Yr	30 Yr
Section 1 of IF	20	1.86%	2.92%	1.85%	2.07%
Section 5 of IF	35	2.92%	5.68%	5.68%	6.56%
Section 6 of IF	35	8.34%	4.12%	6.12%	4.90%
Section 9 of FW	30	2.97%	4.45%	3.43%	3.04%
Section 10 of #1	40	2.94%	3.02%	1.67%	1.86%

The average increases of pavement rehabilitation costs are 3.8, 4.0, 3.8, and 3.7 percent for 15-, 20-, 25-, and 30-year design periods, respectively. It can be seen that there are no significant differences among them regarding the design periods.

Finally, from regression analysis in Chapter 8, for pavement with high remaining life (RL), the initial percent increase of rehabilitation cost is high when the percent ESAL increase is low.

Assuming buses and trucks contribute 85 percent and 15 percent of total ESALs, respectively, when trucks are one percent of ADT. Then, if trucks increase to three percent, which is three times the original volume, the impact of CNG buses will reduce from six percent to

(85 percent x 106 percent + 3 x 15 percent) / (85 percent + 3 x 15 percent) = 3.9 percent ≈ 4 percent.

For instance, under remaining life (RL) = 50 percent and structure type = 1, when the ESAL increase is a low four percent, then the relative increase of the pavement rehabilitation cost is six percent, which is higher than the ESAL increase. This difference arises because pavement with a high remaining life has a relatively low initial pavement rehabilitation cost. This cost is the denominator when calculating the percent increase of cost, thus a small cost increase over a low denominator results in a high percent increase. In the regression formula, the remaining life has a positive regression coefficient of 0.0444, indicating that remaining life (RL) has a small tendency to increase the percentage of rehabilitation cost.

In this chapter, major findings of the study are further developed and the conclusion of the study, along with recommendations, are summarized in Chapter 10.

CHAPTER 10. CONCLUSIONS AND RECOMMENDATIONS

The following are conclusions and recommendations from this study:

1) To design an adequate pavement on a bus route, the trend pattern of passenger occupancy along that route should be considered when choosing an average value of occupancy in ESAL calculations. Based on survey data, route sections in Austin should be categorized into five classes of average occupancy as follows:
   - very dense occupancy sections with an average of 25 passengers,
   - dense occupancy sections with an average of 20 passengers,
   - medium occupancy sections with an average of 15 passengers,
   - low occupancy sections with an average of 10 passengers, and
   - very low occupancy sections with an average of five passengers.
2) Since passengers normally spread over the entire seating area in a bus, the center of gravity of passenger loading can be assumed to be at the geometric center of the seating area. The coefficients of distribution of passenger loading to front axle and rear axle can be assumed as 0.4 and 0.6, respectively.
3) Bus loading contributes the most ESALs on the pavements of bus routes. In Austin, this accounts for 85 percent of applied ESALs on average, and indicates ESALs of bus routes may be as high as five times that of other streets of same ADT level with no buses. In addition, ESALs of bus routes are even greater than those of some freeways. In anticipation of the widespread use of CNG buses, street pavements on bus routes should be designed differently from streets with no bus routes to accommodate the high ESAL applications.
4) Determination of truck traffic in daily street traffic data should be based on the intrinsic characteristics of the city. Traffic growth rate, which is another parameter related to the traffic loading on street pavements, should be determined based on those same characteristics.
5) The impact of CNG fueled bus applications on pavement is expressed by percent increase of ESAL on the bus routes. In the pilot studies, using CNG buses instead of conventional diesel buses on bus routes, ESALs increased by 6.1, 7.3, and 10.9 percent, respectively, for the three routes studied. For the entire Capital Metro route system, the increase of ESALs under CNG bus operation is estimated at five to six percent.

6) For bus routes with high ADT volume or high percent truck traffic in ADT, the impact of CNG bus operation will be relatively lower. For cities with truck traffic volume higher than Austin, the impact could fall below four percent.
7) ESAL-lane-miles and weighted mean ESALs are useful inputs to determine pavement damage level on an entire bus route or bus route system.
8) The impact of CNG bus operation on pavement rehabilitation cost is expressed as a percent increase of the rehabilitation cost. Pilot studies show that the average rehabilitation cost increments are 6.2, 7.1, and 5.0 percent for IF, FW, and #1 bus routes, respectively. For different sections of the bus route, the rehabilitation cost increase varies from 0.0 to 18.6 percent. These estimates can be used as valuable references to estimate other routes. For the entire city bus route system, the estimated overlay rehabilitation cost increase from CNG bus use is about four to five percent. The design period is found to have no significant impact.
9) The regression model and charts given in Chapter 8 can be used as tools for estimating the impact of CNG buses on pavement rehabilitation costs. Results of the cost impact study show that in most cases, the increase of rehabilitation cost is less than the percentage of ESAL increase. Under the same ESAL increment and remaining life, strong pavements have less increase in rehabilitation cost, and the desirability of strengthening city pavements over which CNG buses are scheduled to operate is shown.

Since CNG bus operation is a new practice for most transit authorities, further study may improve the models presented in this study. As more Capital Metro CNG buses are put into service, data should be collected on actual pavement damage over bus routes in order to compare those data with the estimates reported in this study. The curb weight of all CNG buses used by the City of Austin should also be determined, and traffic data collected, especially truck traffic on city streets. When a better range of data are available in the areas of pavement damage, vehicle utilization patterns, traffic data, and improvements to the models reported in this study can be made.

APPENDIX 1. THE ESAL FACTORS OF SIX TYPES OF BUSES (FOR FLEXIBLE PAVEMENT AND UNDER DIFFERENT PT, SN CONDITIONS)

AP 1.1 ESAL FACTOR AT MINIMUM ACCEPTABLE PRESENT SERVICEABILITY INDEX OF PT = 2.0 (WEIGHT UNIT: 1000 LBS)

TMC CNG Bus at Pt = 2.0

		SN=2	2.5	3	3.5	4	4.5	5
# Occupancy	Total Wt.							
0	29.32	1.3501	1.3486	1.3436	1.3381	1.3352	1.3348	1.3362
5	30.07	1.4994	1.4944	1.4858	1.4780	1.4749	1.4759	1.4796
10	30.82	1.6617	1.6527	1.6398	1.6291	1.6255	1.6281	1.6342
15	31.57	1.8376	1.8241	1.8063	1.7921	1.7877	1.7918	1.8008
20	32.32	2.0282	2.0094	1.9859	1.9677	1.9621	1.9678	1.9800
25	33.07	2.2343	2.2096	2.1796	2.1565	2.1494	2.1566	2.1723
30	33.82	2.4568	2.4255	2.3881	2.3593	2.3502	2.3590	2.3784
35	34.57	2.6967	2.6579	2.6122	2.5769	2.5652	2.5754	2.5990
40	35.32	2.9550	2.9079	2.8528	2.8101	2.7953	2.8068	2.8347
43	35.77	3.1192	3.0667	3.0055	2.9578	2.9409	2.9531	2.9837
45	36.07	3.2326	3.1764	3.1109	3.0597	3.0411	3.0538	3.0863
50	36.82	3.5307	3.4643	3.3873	3.3266	3.3035	3.3171	3.3545
55	37.57	3.8504	3.7729	3.6830	3.6118	3.5833	3.5975	3.6400
60	38.32	4.1927	4.1031	3.9991	3.9160	3.8814	3.8958	3.9437
65	39.07	4.5589	4.4560	4.3366	4.2403	4.1986	4.2128	4.2662

Blue Bird CNG Bus at Pt = 2.0

		SN=2	2.5	3	3.5	4	4.5	5
# Occupancy	Total Wt.							
0	25.50	0.8229	0.8300	0.8340	0.8339	0.8308	0.8261	0.8218
5	26.25	0.9236	0.9291	0.9317	0.9309	0.9281	0.9243	0.9210
10	27.00	1.0340	1.0375	1.0382	1.0365	1.0339	1.0312	1.0291
15	27.75	1.1547	1.1558	1.1541	1.1511	1.1487	1.1471	1.1466
20	28.50	1.2864	1.2848	1.2801	1.2753	1.2729	1.2727	1.2740
25	29.25	1.4299	1.4250	1.4168	1.4098	1.4072	1.4084	1.4118
30	30.00	1.5859	1.5772	1.5650	1.5552	1.5522	1.5548	1.5606
35	30.75	1.7553	1.7422	1.7252	1.7120	1.7083	1.7125	1.7211
40	31.50	1.9388	1.9207	1.8982	1.8811	1.8763	1.8821	1.8937
45	32.25	2.1375	2.1137	2.0849	2.0631	2.0568	2.0641	2.0792
50	33.00	2.3520	2.3219	2.2860	2.2587	2.2505	2.2593	2.2781
55	33.75	2.5835	2.5462	2.5023	2.4687	2.4581	2.4683	2.4911
60	34.50	2.8328	2.7876	2.7346	2.6939	2.6802	2.6918	2.7188

GILLIG 1100 Bus at Pt = 2.0

		SN=2	2.5	3	3.5	4	4.5	5
# Occupancy	Total Wt.							
0	28.26	1.2948	1.2922	1.2868	1.2818	1.2797	1.2799	1.2817
5	29.01	1.4389	1.4329	1.4239	1.4166	1.4143	1.4159	1.4199
10	29.76	1.5956	1.5857	1.5725	1.5623	1.5595	1.5626	1.5691
15	30.51	1.7656	1.7513	1.7332	1.7195	1.7159	1.7206	1.7299
20	31.26	1.9499	1.9304	1.9067	1.8889	1.8842	1.8905	1.9029
25	32.01	2.1492	2.1240	2.0939	2.0713	2.0650	2.0728	2.0887
30	32.76	2.3645	2.3329	2.2955	2.2673	2.2590	2.2683	2.2879
35	33.51	2.5968	2.5579	2.5123	2.4777	2.4668	2.4776	2.5012
40	34.26	2.8469	2.8001	2.7453	2.7033	2.6893	2.7013	2.7292
45	35.01	3.1160	3.0602	2.9953	2.9449	2.9272	2.9403	2.9727
47	35.31	3.2291	3.1696	3.1002	3.0463	3.0268	3.0402	3.0746
50	35.76	3.4050	3.3394	3.2632	3.2035	3.1812	3.1951	3.2323
55	36.51	3.7150	3.6387	3.5500	3.4798	3.4522	3.4667	3.5089
60	37.26	4.0471	3.9591	3.8566	3.7747	3.7410	3.7557	3.8031
65	38.01	4.4026	4.3017	4.1842	4.0893	4.0485	4.0630	4.1157
70	38.76	4.7825	4.6676	4.5337	4.4245	4.3756	4.3894	4.4476

GILLIG 1700 Bus at Pt = 2.0

# Occupancy	Total Wt.	SN=2	2.5	3	3.5	4	4.5	5
0	26.38	1.0376	1.0397	1.0395	1.0379	1.0360	1.0340	1.0327
5	27.13	1.1583	1.1579	1.1552	1.1521	1.1503	1.1496	1.1499
10	27.88	1.2901	1.2867	1.2809	1.2760	1.2742	1.2748	1.2770
15	28.63	1.4336	1.4268	1.4173	1.4100	1.4080	1.4100	1.4144
20	29.38	1.5897	1.5789	1.5651	1.5548	1.5523	1.5559	1.5629
25	30.13	1.7590	1.7437	1.7249	1.7112	1.7079	1.7130	1.7228
30	30.88	1.9425	1.9221	1.8976	1.8796	1.8752	1.8819	1.8948
35	31.63	2.1410	2.1149	2.0838	2.0610	2.0549	2.0632	2.0796
39	32.23	2.3113	2.2800	2.2432	2.2158	2.2081	2.2176	2.2369
40	32.38	2.3555	2.3228	2.2845	2.2559	2.2478	2.2576	2.2777
45	33.13	2.5868	2.5469	2.5003	2.4652	2.4544	2.4656	2.4898
50	33.88	2.8359	2.7880	2.7321	2.6896	2.6757	2.6881	2.7165
55	34.63	3.1038	3.0470	2.9810	2.9300	2.9122	2.9257	2.9587
60	35.38	3.3916	3.3251	3.2476	3.1872	3.1648	3.1791	3.2169

GILLIG 1600 Bus at Pt = 2.0

		SN=2	2.5	3	3.5	4	4.5	5
# Occupancy	Total Wt.							
0	25.08	0.9676	0.9698	0.9705	0.9699	0.9684	0.9665	0.9650
5	25.83	1.0814	1.0812	1.0796	1.0776	1.0765	1.0758	1.0757
10	26.58	1.2058	1.2028	1.1982	1.1946	1.1935	1.1941	1.1959
15	27.33	1.3414	1.3351	1.3270	1.3212	1.3201	1.3221	1.3260
20	28.08	1.4890	1.4789	1.4667	1.4582	1.4567	1.4603	1.4666
25	28.83	1.6493	1.6349	1.6179	1.6062	1.6040	1.6092	1.6183
29	29.43	1.7873	1.7690	1.7477	1.7329	1.7300	1.7365	1.7479
30	29.58	1.8232	1.8039	1.7814	1.7658	1.7627	1.7695	1.7815
35	30.33	2.0115	1.9866	1.9580	1.9377	1.9332	1.9416	1.9570
40	31.08	2.2150	2.1840	2.1483	2.1226	2.1163	2.1262	2.1453
45	31.83	2.4347	2.3968	2.3532	2.3213	2.3126	2.3241	2.3470

Dillo (Trolly 900) Bus at Pt = 2.0

# Occupancy	Total Wt.	SN=2	2.5	3	3.5	4	4.5	5
0	20.82	0.2023	0.2126	0.2156	0.2115	0.2043	0.1973	0.1916
5	21.57	0.2322	0.2438	0.2477	0.2436	0.2360	0.2282	0.2219
10	22.32	0.2656	0.2786	0.2835	0.2796	0.2715	0.2629	0.2560
15	23.07	0.3031	0.3173	0.3233	0.3197	0.3111	0.3019	0.2943
20	23.82	0.3449	0.3603	0.3674	0.3642	0.3553	0.3454	0.3372
25	24.57	0.3914	0.4079	0.4162	0.4135	0.4043	0.3938	0.3849
30	25.32	0.4430	0.4605	0.4700	0.4679	0.4586	0.4476	0.4380
35	26.07	0.5002	0.5185	0.5291	0.5277	0.5184	0.5069	0.4969
40	26.82	0.5634	0.5824	0.5940	0.5933	0.5842	0.5724	0.5619
45	27.57	0.6332	0.6526	0.6651	0.6652	0.6563	0.6443	0.6335
50	28.32	0.7100	0.7296	0.7428	0.7437	0.7352	0.7232	0.7122

AP 1.2 ESAL FACTOR AT MINIMUM ACCEPTABLE PRESENT SERVICEABILITY INDEX OF PT = 2.5 (WEIGHT UNIT: 1000 LBS.)

TMC CNG Bus at Pt = 2.5

		SN=2	2.5	3	3.5	4	4.5	5
# Occupancy	Total WT.							
0	29.32	1.3581	1.3574	1.3474	1.3339	1.3253	0.0731	1.3253
5	30.07	1.5020	1.4939	1.4763	1.4579	1.4486	0.0742	1.4563
10	30.82	1.6581	1.6413	1.6149	1.5904	1.5800	0.0754	1.5961
15	31.57	1.8271	1.8005	1.7637	1.7321	1.7200	0.0764	1.7451
20	32.32	2.0099	1.9720	1.9235	1.8834	1.8688	0.0771	1.9035
25	33.07	2.2072	2.1566	2.0947	2.0449	2.0271	0.0775	2.0717
30	33.82	2.4200	2.3551	2.2781	2.2170	2.1951	0.0773	2.2501
35	34.57	2.6491	2.5684	2.4743	2.4004	2.3733	0.0767	2.4390
40	35.32	2.8955	2.7971	2.6841	2.5956	2.5623	0.0754	2.6388
45	36.07	3.1601	3.0422	2.9081	2.8032	2.7625	0.0737	2.8497
50	36.82	3.4440	3.3045	3.1471	3.0238	2.9744	0.0714	3.0723
55	37.57	3.7481	3.5851	3.4019	3.2582	3.1986	0.0686	3.3069
60	38.32	4.0735	3.8847	3.6732	3.5068	3.4357	0.0653	3.5539
65	39.07	4.4214	4.2045	3.9620	3.7706	3.6862	0.0617	3.8138

Blur Bird CNG Bus at Pt = 2.5

		SN=2	2.5	3	3.5	4	4.5	5
# Occupancy	Total WT.							
0	25.50	0.8448	0.8626	0.8719	0.8705	0.8618	0.0631	0.8401
5	26.25	0.9429	0.9572	0.9633	0.9603	0.9522	0.0626	0.9348
10	27.00	1.0501	1.0602	1.0620	1.0568	1.0492	0.0628	1.0370
15	27.75	1.1671	1.1721	1.1687	1.1604	1.1531	0.0637	1.1468
20	28.50	1.2944	1.2934	1.2837	1.2716	1.2642	0.0650	1.2647
25	29.25	1.4329	1.4247	1.4077	1.3908	1.3829	0.0668	1.3908
30	30.00	1.5831	1.5667	1.5411	1.5184	1.5094	0.0687	1.5255
35	30.75	1.7459	1.7201	1.6846	1.6549	1.6442	0.0706	1.6691
40	31.50	1.9220	1.8855	1.8386	1.8007	1.7877	0.0725	1.8220
45	32.25	2.1123	2.0637	2.0039	1.9565	1.9404	0.0741	1.9844
50	33.00	2.3177	2.2554	2.1810	2.1226	2.1025	0.0754	2.1567
55	33.75	2.5388	2.4614	2.3706	2.2997	2.2747	0.0762	2.3393
60	34.50	2.7768	2.6825	2.5735	2.4884	2.4573	0.0765	2.5324

GILLIG 1100 Bus at Pt = 2.5

		SN=2	2.5	3	3.5	4	4.5	5
# Occupancy	Total Wt.							
0	28.26	1.3013	1.2979	1.2865	1.2740	1.2672	0.0605	1.2701
5	29.01	1.4403	1.4297	1.4106	1.3930	1.3857	0.0624	1.3962
10	29.76	1.5911	1.5721	1.5442	1.5206	1.5121	0.0647	1.5308
15	30.51	1.7546	1.7260	1.6879	1.6570	1.6467	0.0670	1.6744
20	31.26	1.9314	1.8919	1.8422	1.8028	1.7900	0.0693	1.8271
25	32.01	2.1223	2.0706	2.0077	1.9585	1.9424	0.0715	1.9894
30	32.76	2.3284	2.2629	2.1851	2.1247	2.1044	0.0734	2.1615
35	33.51	2.5503	2.4695	2.3751	2.3018	2.2763	0.0748	2.3438
40	34.26	2.7890	2.6912	2.5783	2.4906	2.4588	0.0758	2.5367
45	35.01	3.0455	2.9289	2.7954	2.6914	2.6521	0.0762	2.7405
50	35.76	3.3208	3.1835	3.0272	2.9051	2.8570	0.0760	2.9556
55	36.51	3.6159	3.4558	3.2745	3.1322	3.0739	0.0751	3.1824
60	37.26	3.9317	3.7467	3.5380	3.3733	3.3034	0.0737	3.4213
65	38.01	4.2694	4.0574	3.8185	3.6292	3.5460	0.0717	3.6727
70	38.76	4.6302	4.3886	4.1170	3.9006	3.8024	0.0691	3.9372

GILLIG 1700 Bus at Pt = 2.5

		SN=2	2.5	3	3.5	4	4.5	5
# Occupancy	Total Wt.							
0	26.38	1.0509	1.0573	1.0570	1.0520	1.0461	0.0523	1.0377
5	27.13	1.1679	1.1689	1.1629	1.1546	1.1490	0.0531	1.1468
10	27.88	1.2953	1.2899	1.2773	1.2648	1.2590	0.0546	1.2638
15	28.63	1.4337	1.4210	1.4006	1.3829	1.3764	0.0567	1.3890
20	29.38	1.5839	1.5628	1.5333	1.5094	1.5017	0.0591	1.5226
25	30.13	1.7467	1.7159	1.6760	1.6448	1.6352	0.0618	1.6651
30	30.88	1.9228	1.8810	1.8294	1.7895	1.7773	0.0646	1.8167
35	31.63	2.1130	2.0590	1.9939	1.9441	1.9285	0.0673	1.9777
40	32.38	2.3182	2.2504	2.1704	2.1090	2.0891	0.0699	2.1485
45	33.13	2.5392	2.4561	2.3593	2.2850	2.2597	0.0721	2.3295
50	33.88	2.7770	2.6769	2.5614	2.4724	2.4407	0.0739	2.5208
55	34.63	3.0324	2.9136	2.7775	2.6720	2.6326	0.0751	2.7231
60	35.38	3.3066	3.1670	3.0081	2.8843	2.8360	0.0758	2.9365

GILLIG 1600 Bus at Pt = 2.5

# Occupancy	Total Wt.	SN=2	2.5	3	3.5	4	4.5	5
0	25.08	0.9796	0.9856	0.9870	0.9845	0.9801	0.0406	0.9717
5	25.83	1.0900	1.0908	1.0868	1.0813	1.0774	0.0404	1.0750
10	26.58	1.2104	1.2050	1.1946	1.1853	1.1815	0.0411	1.1860
15	27.33	1.3413	1.3289	1.3109	1.2968	1.2927	0.0425	1.3048
20	28.08	1.4836	1.4630	1.4363	1.4164	1.4113	0.0446	1.4317
25	28.83	1.6378	1.6080	1.5713	1.5444	1.5378	0.0472	1.5671
30	29.58	1.8048	1.7647	1.7165	1.6814	1.6726	0.0503	1.7112
35	30.33	1.9853	1.9335	1.8725	1.8279	1.8160	0.0536	1.8644
40	31.08	2.1802	2.1154	2.0400	1.9843	1.9685	0.0570	2.0270
45	31.83	2.3903	2.3110	2.2195	2.1513	2.1305	0.0605	2.1994

Dillo (Trolly 900) Bus at Pt = 2.5

# Occupancy	Total Wt.	SN=2	2.5	3	3.5	4	4.5	5
0	20.82	0.2390	0.2675	0.2760	0.2642	0.2444	0.2258	0.2116
5	21.57	0.2704	0.3021	0.3130	0.3016	0.2805	0.2601	0.2444
10	22.32	0.3053	0.3399	0.3536	0.3428	0.3205	0.2983	0.2811
15	23.07	0.3439	0.3814	0.3979	0.3880	0.3648	0.3409	0.3221
20	23.82	0.3865	0.4267	0.4461	0.4374	0.4134	0.3880	0.3677
25	24.57	0.4336	0.4762	0.4984	0.4912	0.4668	0.4400	0.4182
30	25.32	0.4856	0.5301	0.5551	0.5496	0.5251	0.4971	0.4740
35	26.07	0.5428	0.5889	0.6165	0.6128	0.5885	0.5597	0.5354
40	26.82	0.6057	0.6529	0.6828	0.6810	0.6573	0.6279	0.6028
45	27.57	0.6748	0.7225	0.7543	0.7545	0.7318	0.7022	0.6764
50	28.32	0.7506	0.7982	0.8313	0.8336	0.8120	0.7827	0.7566

APPENDIX 2. INPUT AND OUTPUT DATA FOR ESAL CALCULATION OF IF ROUTE

AP 2.1. NUMBER OF TRUCKS AND BUSES APPLIED ON IF BUS ROUTE (ONE DIRECTION)

Section ID number	ADT volume	% Truck in ADT	Trucks	IF bus	# 5 bus	# 40 bus	ECbus	# 21/22 bus	BRC bus
1	11120	0.8	44	158	0	0	0	0	0
2	6890	0.8	28	158	0	0	0	0	0
3	1930	0.6	6	158	0	0	0	0	0
4	1930	0.8	8	158	0	0	0	0	0
5	4110	0.8	16	158	36	0	0	0	0
6	5260	0.8	21	158	36	0	0	0	0
7	5260	0.8	21	158	36	0	0	0	0
8	5960	0.8	24	158	36	0	0	0	0
9	6280	0.8	25	158	36	0	0	0	0
10	6280	0.8	25	158	36	0	0	0	0
11	6280	0.8	25	158	36	0	0	0	0
12	24100	0.8	96	158	0	100	94	27	22
13	11110	0.8	44	158	0	0	0	0	22

Source: Ref 37, 43

AP 2.2. ESAL UNDER DIESEL BUS OPERATION ON IF ROUTE (ONE DIRECTION)

Section ID number	ESAL of Trucks	ESAL of IF buses	ESAL of #5 buses	ESAL of #40 buses	ESAL of EC buses	ESAL of #21/22 buses	ESAL of BRC buses	ESAL in each seceion
1	22.24	226.40	0.00	0.00	0.00	0.00	0.00	248.64
2	13.78	250.54	0.00	0.00	0.00	0.00	0.00	264.32
3	2.316	250.54	0.00	0.00	0.00	0.00	0.00	252.86
4	3.86	250.54	0.00	0.00	0.00	0.00	0.00	254.40
5	8.22	250.54	51.36	0.00	0.00	0.00	0.00	310.13
6	10.52	276.71	51.36	0.00	0.00	0.00	0.00	338.59
7	10.52	305.00	51.36	0.00	0.00	0.00	0.00	366.89
8	11.92	335.59	56.84	0.00	0.00	0.00	0.00	404.35
9	12.56	335.59	56.84	0.00	0.00	0.00	0.00	404.99
10	12.56	335.59	56.84	0.00	0.00	0.00	0.00	404.99
11	12.56	335.59	56.84	0.00	0.00	0.00	0.00	404.99
12	48.2	335.59	0.00	193.04	164.62	29.19	28.27	798.91
13	22.22	335.59	0.00	0.00	0.00	0.00	28.27	386.08

AP 2.3 ESAL UNDER CNG BUS OPERATION ON IF ROUTE (ONE DIRECTION)

Section ID number	ESAL of Trucks	ESAL of IF buses	ESAL of #5 buses	ESAL of #40 buses	ESAL of EC buses	ESAL of #21/22 buses	ESAL of BRC buses	ESAL in each section
1	22.24	236.12	0.00	0.00	0.00	0.00	0.00	270.88
2	13.78	261.13	0.00	0.00	0.00	0.00	0.00	278.10
3	2.316	261.13	0.00	0.00	0.00	0.00	0.00	255.17
4	3.86	261.13	0.00	0.00	0.00	0.00	0.00	258.26
5	8.22	261.13	65.67	0.00	0.00	0.00	0.00	384.01
6	10.52	288.21	65.67	0.00	0.00	0.00	0.00	414.78
7	10.52	317.49	65.67	0.00	0.00	0.00	0.00	443.08
8	11.92	349.12	72.34	0.00	0.00	0.00	0.00	488.61
9	12.56	349.12	72.34	0.00	0.00	0.00	0.00	489.89
10	12.56	349.12	72.34	0.00	0.00	0.00	0.00	489.89
11	12.56	349.12	72.34	0.00	0.00	0.00	0.00	489.89
12	48.2	349.12	0.00	200.94	171.47	40.35	44.21	1091.98
13	22.22	349.12	0.00	0.00	0.00	0.00	28.27	436.56

APPENDIX 3. INPUT AND OUTPUT DATA FOR ESAL CALCULATION OF FW ROUTE

AP 3.1 NUMBER OF TRUCKS AND BUSES APPLIED ON FW BUS ROUTE (ONE DIRECTION)

Section ID number	ADT volume	% Truck in ADT	Trucks	#Bus FW	#Bus 5
1	6200	0.6	19	105	0
2	5910	0.6	18	105	0
3	5600	0.6	17	105	0
4	7950	0.6	24	105	0
5	30630	1	153	105	0
6	30180	1	151	105	0
7	27650	1	138	105	0
8	25070	1	125	105	0
9	25790	1	129	105	0
10	26120	1	131	105	0
11	30360	1	152	105	0
12	20690	0.8	83	105	36
13	5720	0.6	17	105	0
14	5720	0.6	17	105	0

#Bus 40	#Bus EC	#B 21/22	#B. BRC	#B #1	#B LX	#B 19
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	25
0	0	0	0	0	0	25
0	0	0	0	0	0	0
0	0	27	22	0	32	0
0	0	0	22	0	32	0
0	0	0	22	84	32	0
0	0	27	22	84	32	0
0	0	27	22	84	32	0
0	0	27	22	84	32	0
100	94	27	22	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

AP 3.2. ESAL UNDER DIESEL BUS OPERATION ON FW ROUTE (ONE DIRECTION)

Section ID number	ESAL of Trucks	ESAL of FW	ESAL of #5	ESAL of #40	ESAL of EC	ESAL of #21/22	ESAL of BRC	ESAL of #1	ESAL of LX	ESAL of #19	ESAL in each section
1	7.44	166.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	173.94
2	7.092	166.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	173.59
3	6.72	166.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30.07	203.29
4	9.54	166.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30.07	206.11
5	122.52	177.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	299.75
6	120.72	177.23	0.00	0.00	0.00	29.34	28.24	0.00	58.95	0.00	414.48
7	82.95	177.23	0.00	0.00	0.00	0.00	28.24	0.00	58.95	0.00	347.37
8	75.21	177.23	0.00	0.00	0.00	0.00	28.24	168.65	58.95	0.00	508.28
9	77.37	177.23	0.00	0.00	0.00	29.34	28.24	168.65	58.95	0.00	539.78
10	78.36	177.23	0.00	0.00	0.00	29.34	28.24	168.65	58.95	0.00	540.77
11	121.44	177.23	0.00	0.00	0.00	29.34	28.24	168.65	58.95	0.00	583.85
12	49.656	177.23	56.84	193.04	164.62	29.19	28.27	0.00	0.00	0.00	698.85
13	6.864	183.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	190.75
14	6.864	183.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	190.75

AP 3.3. ESAL UNDER CNG BUS OPERATION ON FW BUS ROUTE (ONE DIRECTION)

Section ID number	ESAL of Trucks	ESAL of FW	ESAL of #5	ESAL of #40	ESAL of EC	ESAL of #21/22	ESAL of BRC	ESAL of #1	ESAL of LX	ESAL of #19	ESAL in each section
1	7.44	173.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	180.974
2	7.092	173.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	180.626
3	6.72	173.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	41.32	221.571
4	9.54	173.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	41.32	224.391
5	122.52	185.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	307.709
6	120.72	185.19	0.00	0.00	0.00	39.86	42.32	0.00	61.55	0.00	449.638
7	82.95	185.19	0.00	0.00	0.00	0.00	42.32	0.00	61.55	0.00	372.008
8	75.21	185.19	0.00	0.00	0.00	0.00	42.32	175.95	61.55	0.00	540.222
9	77.37	185.19	0.00	0.00	0.00	39.86	42.32	175.95	61.55	0.00	582.242
10	78.36	185.19	0.00	0.00	0.00	39.86	42.32	175.95	61.55	0.00	583.232
11	121.44	185.19	0.00	0.00	0.00	39.86	42.32	175.95	61.55	0.00	626.312
12	49.656	185.19	72.34	200.94	171.47	39.86	44.21	0.00	0.00	0.00	763.655
13	6.864	191.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	198.395
14	6.864	191.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	198.395

APPENDIX 4. INPUT AND OUTPUT DATA FOR ESAL CALCULATION OF #1 ROUTE

AP 4.1. NUMBER OF TRUCKS AND BUSES APPLIED ON #1 BUS ROUTE (ONE DIRECTION)

Section Number	ADT volume	Percent Truck in ADT	Trucks	#1 bus	# 5 bus	# 40 bus	EC bus	# 21/22 bus	FW bus	#3 bus	LX bus	#19 bus
1	19650	1	98	84	36	0	0	0	0	0	0	25
2	19120	1	96	84	36	0	0	0	0	0	0	0
3	8660	0.8	35	84	36	0	0	0	0	43	32	25
4	13020	0.8	52	84	36	0	0	0	0	43	32	25
5	9240	0.8	37	84	36	0	0	0	0	0	32	0
6	16130	0.8	65	84	36	0	0	0	0	43	32	25
7	9930	0.8	40	84	36	0	0	0	0	0	32	0
8	24710	1	124	84	36	0	0	0	0	0	32	0
9	30326	1	152	84	36	100	94	0	0	0	32	0
10	26120	1	131	84	0	0	0	27	105	0	32	0
11	25790	1	129	84	0	0	0	27	105	0	32	0
12	22130	1	111	84	0	0	0	0	0	0	0	0
13	30530	1	153	84	0	0	0	0	0	0	0	0
14	40820	1	204	84	0	0	0	0	0	0	0	0
15	35100	1	176	84	0	0	0	0	0	0	0	0
16	37280	1	186	84	0	0	0	0	0	0	0	0
17	40170	1	201	84	0	0	0	0	0	0	0	0
18	15390	1	77	84	0	0	0	0	0	0	0	0
19	13130	1	66	84	0	0	0	0	0	0	0	0
20	13130	1	66	84	0	0	0	0	0	0	0	0

AP 4.1 NUMBER OF TRUCKS AND BUSES APPLIED ON #1 BUS ROUTE (ONE DIRECTION) ***(Continued)***

#CC-UT	#B ACC	#B 9	#B 2	#B 30	#B 6	#B 12	#B 15	#B C/C	#B 37	#B 25	#B 42	#B 32	#B 8
0	0	22	40	0	38	18	41	59	0	0	0	0	0
0	0	22	0	31	38	0	0	59	0	0	0	0	0
0	0	22	40	31	38	18	41	0	36	0	0	0	0
0	0	22	0	0	0	0	0	0	0	0	0	0	0
0	64	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	31	0	0	0	59	0	0	0	0	0
0	64	0	0	31	0	0	0	0	0	0	0	0	0
0	64	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	21	51
0	0	0	0	0	0	0	0	0	0	0	24	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	32	24	0	0

AP 4.2 ESAL OF TRUCKS AND BUSES UNDER DIESEL BUS OPERATION ON #1 BUS ROUTE (ONE DIRECTION)

Section number	Trucks	#1	#5	#40	ECbus	#21/22	FW	#3	LXbus	#19	CCUT bus	ACC bus
1	58.95	154.74	50.42	0.00	0.00	0.00	0.00	0.00	0.00	30.07	0.00	0.00
2	57.36	154.74	50.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	17.32	168.59	50.42	0.00	0.00	0.00	0.00	74.53	58.95	30.07	0.00	0.00
4	26.04	168.59	50.42	0.00	0.00	0.00	0.00	74.53	58.95	30.07	0.00	0.00
5	18.48	168.59	50.42	0.00	0.00	0.00	0.00	0.00	58.95	0.00	0.00	17.83
6	32.26	168.59	50.42	0.00	0.00	0.00	0.00	74.53	58.95	30.07	0.00	0.00
7	19.86	168.59	50.42	0.00	0.00	0.00	0.00	0.00	58.95	0.00	0.00	17.83
8	98.84	168.59	50.42	0.00	0.00	0.00	0.00	0.00	58.95	0.00	0.00	17.83
9	121.30	168.59	55.20	184.22	158.66	0.00	0.00	0.00	58.95	0.00	15.04	0.00
10	104.48	168.59	0.00	0.00	0.00	29.34	177.23	0.00	58.95	0.00	0.00	0.00
11	103.16	168.59	0.00	0.00	0.00	29.34	177.23	0.00	58.95	0.00	0.00	0.00
12	88.52	154.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	122.12	154.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	163.28	141.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	140.4	141.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	149.12	129.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	160.68	118.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	61.56	118.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	52.52	118.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	52.52	118.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

AP 4.2 ESAL OF TRUCKS AND BUSES UNDER DIESEL BUS OPERATION ON #1 BUS ROUTE (ONE DIRECTION) *(Continued)*

#9	#2	#30	#6	#12	#15	C/C bus	#37	#25	#42	#32	#8	Total ESAL
28.84	56.02	0.00	64.14	25.21	57.42	16.44	0.00	0.00	0.00	0.00	0.00	542.26
28.84	0.00	43.42	64.14	0.00	0.00	16.44	0.00	0.00	0.00	0.00	0.00	415.36
28.84	56.02	43.42	64.14	25.21	57.42	0.00	60.76	0.00	0.00	0.00	0.00	735.70
28.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	437.44
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	314.27
0.00	0.00	43.42	0.00	0.00	0.00	16.44	0.00	0.00	0.00	0.00	0.00	474.67
0.00	0.00	43.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	359.07
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	394.63
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	761.97
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	538.59
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	537.27
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	243.26
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	276.86
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	305.06
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.09	86.08	393.35
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	26.08	0.00	0.00	304.92
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	279.17
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	180.05
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	171.01
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	54.01	26.08	0.00	0.00	251.11

AP 4.3 ESAL OF TRUCKS AND BUSES UNDER CNG BUS (REMAIN DILLO BUS) OPERATION ON #1 ROUTE (ONE DIRECTION) (ALTERNATIVE 1)

Section number	Trucks	#1	#5	#40	EC bus	#21/22	FW bus	#3	LX bus	#19	CCUT bus	ACC bus
1	58.95	161.57	63.49	0.00	0.00	0.00	0.00	0.00	0.00	41.32	0.00	0.00
2	57.36	161.57	63.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	17.32	175.95	63.49	0.00	0.00	0.00	0.00	78.44	61.55	41.32	0.00	0.00
4	26.04	175.95	63.49	0.00	0.00	0.00	0.00	78.44	61.55	41.32	0.00	0.00
5	18.48	175.95	63.49	0.00	0.00	0.00	0.00	0.00	61.55	0.00	0.00	17.83
6	32.26	175.95	63.49	0.00	0.00	0.00	0.00	78.44	61.55	41.32	0.00	0.00
7	19.86	175.95	63.49	0.00	0.00	0.00	0.00	0.00	61.55	0.00	0.00	17.83
8	98.84	175.95	63.49	0.00	0.00	0.00	0.00	0.00	61.55	0.00	0.00	17.83
9	121.30	175.95	69.25	192.35	165.79	0.00	0.00	0.00	61.55	0.00	15.04	0.00
10	104.48	175.95	0.00	0.00	0.00	39.86	185.19	0.00	61.55	0.00	0.00	0.00
11	103.16	175.95	0.00	0.00	0.00	39.86	185.19	0.00	61.55	0.00	0.00	0.00
12	88.52	161.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	122.12	161.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	163.28	148.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	140.4	148.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	149.12	135.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	160.68	124.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	61.56	124.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	52.52	124.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	52.52	124.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

AP 4.3 ESAL OF TRUCKS AND BUSES UNDER CNG BUS (REMAIN DILLO BUS) OPERATION ON #1 ROUTE (ONE DIRECTION) (ALTERNATIVE 1) *(Continued)*

#9	#2	#30	#6	#12	#15	C/C bus	#37	#25	#42	#32	#8	Total ESAL
38.80	70.55	0.00	67.02	31.75	72.31	16.44	0.00	0.00	0.00	0.00	0.00	622.20
38.80	0.00	54.67	67.02	0.00	0.00	16.44	0.00	0.00	0.00	0.00	0.00	459.36
38.80	70.55	54.67	67.02	31.75	72.31	0.00	63.49	0.00	0.00	0.00	0.00	836.67
38.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	485.60
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	337.31
0.00	0.00	54.67	0.00	0.00	0.00	16.44	0.00	0.00	0.00	0.00	0.00	524.13
0.00	0.00	54.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	393.37
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	417.67
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	801.24
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	567.04
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	565.72
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	250.09
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	283.69
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	311.43
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.09	86.08	399.72
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35.43	0.00	0.00	320.20
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	284.69
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	185.57
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	176.53
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	56.44	35.43	0.00	0.00	268.40

AP 4.4. ESAL OF TRUCKS AND BUSES UNDER CNG BUS OPERATION (FOR ALL ROUTES) ON #1 ROUTE (ONE DIRECTION) (ALTERNATIVE 2)

Section number	Trucks	#1	#5	#40	EC bus	#21/22	FW bus	#3	LX bus	#19	CCUT bus	ACC
1	58.95	161.57	63.49	0.00	0.00	0.00	0.00	0.00	0.00	41.32	0.00	0
2	57.36	161.57	63.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	17.32	175.95	63.49	0.00	0.00	0.00	0.00	78.44	61.55	41.32	0.00	0.00
4	26.04	175.95	63.49	0.00	0.00	0.00	0.00	78.44	61.55	41.32	0.00	0.00
5	18.48	175.95	63.49	0.00	0.00	0.00	0.00	0.00	61.55	0.00	0.00	103.35
6	32.26	175.95	63.49	0.00	0.00	0.00	0.00	78.44	61.55	41.32	0.00	0.00
7	19.86	175.95	63.49	0.00	0.00	0.00	0.00	0.00	61.55	0.00	0.00	103.35
8	98.84	175.95	63.49	0.00	0.00	0.00	0.00	0.00	61.55	0.00	0.00	103.35
9	121.30	175.95	69.25	192.35	165.79	0.00	0.00	0.00	61.55	0.00	87.20	0.00
10	104.48	175.95	0.00	0.00	0.00	39.86	185.19	0.00	61.55	0.00	0.00	0.000.0
11	103.16	175.95	0.00	0.00	0.00	39.86	185.19	0.00	61.55	0.00	0.00	0.00
12	88.52	161.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	122.12	161.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	163.28	148.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	140.4	148.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	149.12	135.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	160.68	124.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	61.56	124.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	52.52	124.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	52.52	124.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

AP 4.4 ESAL OF TRUCKS AND BUSES UNDER CNG BUS OPERATION (FOR ALL ROUTES) ON #1 ROUTE (ONE DIRECTION) (ALTERNATIVE 2) *(Continued)*

#9	#2	#30	#6	#12	#15	C/C bus	#37	#25	#42	#32	#8	Total ESAL
38.80	70.55	0.00	67.02	31.75	72.31	95.28	0.00	0.00	0.00	0.00	0.00	701.04
38.80	0.00	54.67	67.02	0.00	0.00	95.28	0.00	0.00	0.00	0.00	0.00	538.20
38.80	70.55	54.67	67.02	31.75	72.31	0.00	63.49	0.00	0.00	0.00	0.00	836.67
38.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	485.60
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	422.83
0.00	0.00	54.67	0.00	0.00	0.00	95.28	0.00	0.00	0.00	0.00	0.00	602.97
0.00	0.00	54.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	478.89
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	503.19
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	873.40
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	567.04
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	565.72
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	250.09
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	283.69
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	311.43
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33.91	82.36	399.72
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35.43	0.00	0.00	320.20
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	284.69
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	185.57
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	176.53
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	56.44	35.43	0.00	0.00	268.40

APPENDIX 5. LOAD INPUT DATA FOR REHABILITATION COST ANALYSIS OF IF, FW, AND #1 BUS ROUTES

AP 5.1 IF BUS ROUTE UNDER DIESEL BUS OPERATION

Sections ID number	ADT	Trucks in design lane	Truck ESAL	Buses in design lane	Bus ESAL	Percent (Trucks+ Buses) in ADT	Total ESAL of T. & B.	Average ESAL of T. & B.
1	11120	44	22.24	158	226	3.64%	248.638	1.22796
2	6890	28	13.78	158	251	5.39%	264.321	1.42445
3	1930	6	2.316	158	251	16.97%	252.857	1.54379
4	1930	8	3.86	158	251	17.17%	254.401	1.53512
5	4110	16	8.22	194	302	10.24%	310.125	1.4737
6	5260	21	10.52	194	328	8.18%	338.590	1.57455
7	5260	21	10.52	194	356	8.18%	366.888	1.70614
8	5960	24	11.92	194	392	7.31%	404.352	1.85619
9	6280	25	12.56	194	392	6.98%	404.992	1.84827
10	6280	25	12.56	194	392	6.98%	404.992	1.84827
11	6280	25	12.56	194	392	6.98%	404.992	1.84827
12	24100	96	48.2	401	751	4.13%	798.912	1.60618
13	11110	44	22.22	180	364	4.04%	386.078	1.72018

AP 5.2 IF BUS ROUTE UNDER CNG BUS OPERATION

Sections ID number	ADT	Trucks in design lane	Truck ESAL	Buses in design lane	Bus ESAL	Percent (Trucks+ Buses) in ADT	Total ESAL of T. & B.	Average ESAL of T. & B.
1	11120	44	22.24	158	236	3.64%	258.355	1.27595
2	6890	28	13.78	158	261	5.39%	274.907	1.48150
3	1930	6	2.316	158	261	16.97%	263.443	1.60842
4	1930	8	3.86	158	261	17.17%	264.987	1.59900
5	4110	16	8.22	194	327	10.24%	335.014	1.59197
6	5260	21	10.52	194	354	8.18%	364.395	1.69455
7	5260	21	10.52	194	383	8.18%	393.673	1.83070
8	5960	24	11.92	194	421	7.31%	433.375	1.98942
9	6280	25	12.56	194	421	6.98%	434.015	1.98072
10	6280	25	12.56	194	421	6.98%	434.015	1.98072
11	6280	25	12.56	194	421	6.98%	434.015	1.98072
12	24100	96	48.2	401	806	4.13%	854.278	1.71749
13	11110	44	22.22	180	377	4.04%	399.602	1.78044

AP 5.3 FW BUS UNDER DIESEL BUS OPERATION

Sections ID number	ADT	Trucks in design lane	Truck ESAL	Buses in design lane	Bus ESAL	Percent (Trucks+ Buses) in ADT	Total ESAL of T. & B.	Average ESAL of T. & B.
1	6200	19	7.44	105	166.50	3.99%	173.939	1.40727
2	5910	18	7.09	105	166.50	4.15%	173.591	1.41441
3	5600	17	6.72	130	196.57	5.24%	203.289	1.38480
4	7950	24	9.54	130	196.57	3.87%	206.109	1.33967
5	30630	153	122.52	105	177.23	1.69%	299.750	1.16114
6	30180	151	120.72	186	293.76	2.23%	414.485	1.23029
7	27650	138	82.95	159	264.42	2.15%	347.371	1.16862
8	25070	125	75.21	243	433.07	2.94%	508.278	1.37988
9	25790	129	77.37	270	462.41	3.09%	539.782	1.35301
10	26120	131	78.36	270	462.41	3.07%	540.772	1.34990
11	30360	152	121.44	270	462.41	2.78%	583.852	1.38419
12	20690	83	49.66	384	649.19	4.51%	698.846	1.49723
13	5720	17	6.86	105	183.89	4.27%	190.751	1.56148
14	5720	17	6.86	105	183.887	4.27%	190.751	1.56148

AP 5.4. FW BUS ROUTE UNDER CNG BUS OPERATION

Sections ID number	ADT	Trucks in design lane	Truck ESAL	Buses in design lane	Bus ESAL	Percent (Trucks+ Buses) in ADT	Total ESAL of T. & B.	Average ESAL of T. & B.
1	6200	19	7.44	105	173.53	3.99%	180.974	1.46419
2	5910	18	7.09	105	173.53	4.15%	180.626	1.47173
3	5600	17	6.72	130	214.85	5.24%	221.571	1.50934
4	7950	24	9.54	130	214.85	3.87%	224.391	1.45851
5	30630	153	122.52	105	185.19	1.69%	307.709	1.19198
6	30180	151	120.72	186	328.92	2.23%	449.638	1.33463
7	27650	138	82.95	159	289.06	2.15%	372.008	1.25150
8	25070	125	75.21	243	465.01	2.94%	540.222	1.46660
9	25790	129	77.37	270	504.87	3.09%	582.242	1.45944
10	26120	131	78.36	270	504.87	3.07%	583.232	1.45590
11	30360	152	121.44	270	504.87	2.78%	626.312	1.48486
12	20690	83	49.66	384	714.00	4.51%	763.655	1.63608
13	5720	17	6.86	105	191.53	4.27%	198.395	1.62405
14	5720	17	6.86	105	191.531	4.27%	198.395	1.62405

AP 5.5. #1 BUS ROUTE UNDER DIESEL BUS OPERATION

Sections ID number	ADT	Trucks in design lane	Truck ESAL	Buses in design lane	Bus ESAL	Percent (Trucks+ Buses) in ADT	Total ESAL of T. & B.	Average ESAL of T. & B.
1	19650	98	58.95	363	483	4.69%	542.263	1.17564
2	19120	96	57.36	270	358	3.82%	415.362	1.13611
3	8660	35	17.32	446	718	11.10%	735.7	1.53067
4	13020	52	26.04	242	411	4.52%	437.437	1.48748
5	9240	37	18.48	216	296	5.48%	314.27	1.24237
6	16130	65	32.26	310	442	4.64%	474.674	1.26742
7	9930	40	19.86	247	339	5.77%	359.069	1.25233
8	24710	124	98.84	216	296	2.75%	394.63	1.16222
9	30326	152	121.304	400	641	3.64%	761.968	1.3813
10	26120	131	104.48	248	434	2.90%	538.592	1.42259
11	25790	129	103.16	248	434	2.92%	537.272	1.42531
12	22130	111	88.52	84	155	1.76%	243.265	1.24975
13	30530	153	122.12	84	155	1.55%	276.865	1.16993
14	40820	204	163.28	84	142	1.41%	305.064	1.05888
15	35100	176	140.4	156	253	1.89%	393.353	1.18659
16	37280	186	149.12	108	156	1.58%	304.916	1.03572
17	40170	201	160.68	84	118	1.42%	279.17	0.98006
18	15390	77	61.56	84	118	2.09%	180.05	1.11867
19	13130	66	52.52	84	118	2.28%	171.01	1.14274
20	13130	66	52.52	140	199	3.13%	251.106	1.22104

AP 5.6 . #1 BUS UNDER CNG BUS OPERATION

Sections ID number	ADT	Trucks in design lane	Truck ESAL	Buses in design lane	Bus ESAL	Percent (Trucks+ Buses) in ADT	Total ESAL of T. & B.	Average ESAL of T. & B.
1	19650	98	58.95	363	642	4.69%	701.042	1.51987
2	19120	96	57.36	270	481	3.82%	538.203	1.47211
3	8660	35	17.32	446	819	11.10%	836.67	1.74074
4	13020	52	26.04	242	460	4.52%	485.595	1.65124
5	9240	37	18.48	216	404	5.48%	422.834	1.67154
6	16130	65	32.26	310	571	4.64%	602.968	1.60997
7	9930	40	19.86	247	459	5.77%	478.888	1.67023
8	24710	124	98.84	216	404	2.75%	503.194	1.48194
9	30326	152	121.304	400	752	3.64%	873.399	1.58331
10	26120	131	104.48	248	463	2.90%	567.035	1.49772
11	25790	129	103.16	248	463	2.92%	565.715	1.50077
12	22130	111	88.52	84	162	1.76%	250.094	1.28484
13	30530	153	122.12	84	162	1.55%	283.694	1.19879
14	40820	204	163.28	84	148	1.41%	311.431	1.08098
15	35100	176	140.4	156	259	1.89%	412.412	1.24408
16	37280	186	149.12	108	171	1.58%	320.203	1.08765
17	40170	201	160.68	84	124	1.42%	284.689	0.99944
18	15390	77	61.56	84	124	2.09%	185.569	1.15296
19	13130	66	52.52	84	124	2.28%	176.529	1.17961
20	13130	66	52.52	140	216	3.13%	268.399	1.30512

APPENDIX 6. SAS PROGRAM AND OUTPUT

AP 6.1. SAS Program: The Statistical Analysis of the Rehabilitation Cost Data

```
FILENAME INFO 'CNGCOST DATA A';
OPTIONS LS=80 NOCENTER NODATE;

DATA COST;
 INFILE INFO;
 INPUT ID $ 1-4 LENGTH WIDTH STRUCT RL ESALEVEL ESALINCR COSTINCR;

PROC SORT DATA=COST;
 BY RL ESALINCR;

PROC PRINT DATA=COST;

PROC UNIVARIATE DATA=COST;
 VAR RL ESALEVEL ESALINCR COSTINCR;

PROC CORR DATA=COST;
 VAR COSTINCR ESALINCR RL ESALEVEL STRUCT WIDTH LENGTH;

PROC GLM DATA=COST;
 MODEL COSTINCR=LENGTH WIDTH STRUCT RL ESALEVEL ESALINCR;

PROC GLM DATA=COST;
 MODEL COSTINCR=RL STRUCT ESALINCR;

PROC PLOT DATA=COST;
 PLOT COSTINCR * ESALINCR = '$'/VPOS = 16;
```

AP 6.2. SAS Output : Rehabilitation Cost Increase under CNG Bus Operation

1The SAS System

OBS	ID	LENGTH	WIDTH	STRUCT	RL	ESALEVEL	ESALINCR	COSTINCR
1	I-8	0.108	57	3	10	3.173	27.5	6.3
2	IF13	0.297	58	2	15	3.102	3.5	2.6
3	IF1	0.210	27	2	20	1.997	3.9	2.1
4	FW14	0.134	50	2	20	1.532	4.0	1.8
5	IF4	0.225	27	1	20	2.044	4.2	2.9
6	IF10	0.078	37	2	20	3.255	7.2	6.9
7	I-7	0.230	57	3	20	2.883	33/4	14.6
8	FW2A	0.156	37	2	25	1.394	4.1	3.6
9	I-4B	0.138	47	3	25	3.517	11.0	8.9
10	I-5	0.230	37	3	25	2.527	34.6	18.6
11	IF3	0.308	27	1	30	2.032	4.1	2.3
12	FW8	0.190	60	3	30	4.087	6.3	3.1
13	FW9	0.388	60	3	30	4.333	7.8	5.5
14	I-4A	0.207	57	3	30	3.517	11.0	5.0
15	I-2	0.335	61	3	30	3.334	29.6	12.8
16	IF6	0.200	37	2	35	2.723	7.6	5.7
17	IF5	0.438	37	2	35	2.493	8.0	6.4
18	FW13	0.153	27	2	40	1.532	4.0	4.8
19	FW11	0.153	60	3	40	4.694	7.3	4.3
20	FW10	2.255	60	3	40	4.350	7.9	3.3
21	FW3	0.213	41	2	40	1.633	8.9	9.8
22	I-9	0.737	60	3	40	6.126	14.6	8.5
23	I-6	0.345	57	3	40	3.811	27.1	11.7
24	I-3B	0.067	40	3	45	5.914	13.7	3.3
25	I-17	0.130	60	3	50	2.246	2.0	0.7
26	I-18	0.300	41	2	50	1.446	3.0	0.0
27	I-16	1.400	60	3	50	2.452	5.0	2.3
28	FW7	0.342	57	3	50	2.793	7.1	5.0
29	I-3C	0.067	46	3	50	6.725	13.7	4.7
30	FW6A	0.257	41	3	55	3.327	8.5	6.5
31	FW2B	0.313	41	2	60	1.394	4.1	9.6
32	IF8	0.255	37	2	60	3.249	7.2	7.5
33	IF9	0.131	37	2	60	3.255	7.2	4.6
34	IF7	0.190	37	2	60	2.950	7.3	10.9
35	I-1	0.340	61	3	60	4.351	29.4	15.6
36	I-12	0.625	60	3	65	1.956	2.8	4.5
37	I-3A	0.089	68	3	65	5.914	13.7	11.1
38	I-14	0.930	60	3	70	2.449	2.1	1.7
39	I13B	0.740	60	3	70	2.225	2.5	2.3
40	FW5	0.291	62	3	70	2.415	2.7	2.5
41	IF2	0.308	37	2	70	2.125	4.0	6.3
42	I-15	0.808	60	3	70	3.164	4.8	0.7
43	I-19	0.130	41	2	80	1.375	3.3	0.4
44	FW6B	0.703	57	3	80	3.327	8.5	6.5
45	I13A	0.398	37	3	85	2.225	2.5	3.2

1The SAS System

Univariate Procedure

Variable=RL

Moments

N	45	Sum Wgts	45
Mean	45.22222	Sum	2035
Std Dev	19.79886	Variance	391.9949
Skewness	0.181579	Kurtosis	-1.00134
USS	109275	CSS	17247.78
CV	43.78127	Std Mean	2.95144
T:Mean=0	15.32209	Pr>|T|	0.0001
Num ^= 0	45	Num > 0	45
M(Sign)	22.5	Pr>=|M|	0.0001
Sgn Rank	517.5	Pr>=|S|	0.0001

Quantiles(Def=5)

100% Max	85	99%	85
75% Q3	60	95%	80
50% Med	40	90%	70
25% Q1	30	10%	20
0% Min	10	5%	20
		1%	10
Range	75		
Q3-Q1	30		
Mode	40		

Extremes

Lowest	Obs	Highest	Obs
10(	1)	70(	41)
15(	2)	70(	42)
20(	7)	80(	43)
20(	6)	80(	44)
20(	5)	85(	45)

1The SAS System

Univariate Procedure

Variable=ESALEVEL

Moments

N	45	Sum Wgts	45
Mean	3.052578	Sum 1	37.366
Std Dev	1.315955	Variance	1.731736
Skewness	1.066076	Kurtosis	0.904911
USS	495.5168	CSS	76.1964
CV	43.10962	Std Mean	0.196171
T:Mean=0	15.56081	Pr>|T|	0.0001

Num ^= 0	45	Num > 0	45
M(Sign)	22.5	Pr>=|M|	0.0001
Sgn Rank	517.5	Pr>=|S|	0.0001

Quantiles(Def=5)

100% Max	6.725	99%	6.725
75% Q3	3.517	95%	5.914
50% Med	2.883	90%	4.694
25% Q1	2.125	10%	1.532
0% Min	1.375	5%	1.394
		1%	1.375
Range	5.35		
Q3-Q1	1.392		
Mode	1.394		

Extremes

Lowest	Obs	Highest	Obs
1.375(	43)	4.694(	19)
1.394(	31)	5.914(	24)
1.394(	8)	5.914(	37)
1.446(	26)	6.126(	22)
1.532(	18)	6.725(	29)

1The SAS System

Univariate Procedure

Variable=ESALINCR

Moments

N	45	Sum Wgts	45
Mean	9.615556	Sum	432.7
Std Dev	8.880391	Variance	78.86134
Skewness	1.746836	Kurtosis	2.018511
USS	7630.55	CSS	3469.899
CV	92.35442	Std Mean	1.323811
T:Mean=0	7.263544	Pr>|T|	0.0001
Num ^= 0	45	Num > 0	45
M(Sign)	22.5	Pr>=|M|	0.0001
Sgn Rank	517.5	Pr>=|S|	0.0001

Quantiles(Def=5)

100% Max	34.6	99%	34.6
75% Q3	11	95%	29.6
50% Med	7.2	90%	27.5
25% Q1	4	10%	2.7
0% Min	2	5%	2.5
		1%	2
Range	32.6		
Q3-Q1	7		
Mode	4		

Extremes

Lowest	Obs	Highest	Obs
2(	25)	27.5(	1)
2.1(	38)	29.4(	35)
2.5(	45)	29.6(	15)
2.5(	39)	33.4(	7)
2.7(	40)	34.6(	10)

1The SAS System

Univariate Procedure

Variable=COSTINCR

Moments

N	45	Sum Wgts	45
Mean	5.808889	Sum	261.4
Std Dev	4.254614	Variance	18.10174
Skewness	1.109053	Kurtosis	0.969972
USS	2314.92	CSS	796.4764
CV	73.24316	Std Mean	0.63424
T:Mean=0	9.158813	Pr>|T|	0.0001
Num ^= 0	44	Num > 0	44
M(Sign)	22	Pr>=|M|	0.0001
Sgn Rank	495	Pr>=|S|	0.0001

Quantiles(Def=5)

100% Max	18.6	99%	18.6
75% Q3	7.5	95%	14.6
50% Med	4.8	90%	11.7
25% Q1	2.6	10%	1.7
0% Min	0	5%	0.7
		1%	0
Range	18.6		
Q3-Q1	4.9		
Mode	2.3		

Extremes

Lowest	Obs	Highest	Obs
0(	26)	11.7(	23)
0.4(	43)	12.8(	15)
0.7(	42)	14.6(	7)
0.7(	25)	15.6(	35)
1.7(	38)	18.6(	10)

1The SAS System

Correlation Analysis

7 'VAR' Variables: COSTINCR ESALINCR RL ESALEVEL STRUCT WIDTH LENGTH

Simple Statistics

Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
COSTINCR	45	5.80889	4.25461	261.40000	0	18.60000
ESALINCR	45	9.61556	8.88039	432.70000	2.00000	34.60000
RL	45	45.22222	19.79886	2035	10.00000	85.00000
ESALEVEL	45	3.05258	1.31595	137.36600	1.37500	6.72500
STRUCT	45	2.55556	0.58603	115.00000	1.00000	3.00000
WIDTH	45	48.40000	12.04990	2178	27.00000	68.00000
LENGTH	45	0.36760	0.39018	16.54200	0.06700	2.25500

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 45

	COSTINCR	ESALINCR	RL	ESALEVEL	STRUCT	WIDTH	LENGTH
COSTINCR	1.00000	0.81030	-0.15624	0.24223	0.20762	0.06310	-0.17914
	0.0	0.0001	0.3054	0.1089	0.1711	0.6805	0.2390
ESALINCR	0.81030	1.00000	-0.32958	0.36829	0.38610	0.22679	-0.13130
	0.0001	0.0	0.0270	0.0128	0.0088	0.1341	0.3899
RL	-0.15624	-0.32958	1.00000	-0.03369	0.22417	0.14680	0.21368
	0.3054	0.0270	0.0	0.8261	0.1388	0.3359	0.1587
ESALEVEL	0.24223	0.36829	-0.03369	1.00000	0.51410	0.41176	0.04846
	0.1089	0.0128	0.8261	0.0	0.0003	0.0050	0.7519
STRUCT	0.20762	0.38610	0.22417	0.51410	1.00000	0.76598	0.27632
	0.1711	0.0088	0.1388	0.0003	0.0	0.0001	0.0662
WIDTH	0.06310	0.22679	0.14680	0.41176	0.76598	1.00000	0.36060
	0.6805	0.1341	0.3359	0.0050	0.0001	0.0	0.0150
LENGTH	-0.17914	-0.13130	0.21368	0.04846	0.27632	0.36060	1.00000
	0.2390	0.3899	0.1587	0.7519	0.0662	0.0150	0.0

1The SAS System

General Linear Models Procedure

Number of observations in data set = 45

1The SAS System

General Linear Models Procedure

Dependent Variable: COSTINCR

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	560.91150047	93.48525008	15.08	0.0001
Error	38	235.56494397	6.19907747		
Corrected Total	44	796.47644444			

R-Square	C.V.	Root MSE	COSTINCR Mean
0.704241	42.86181	2.4897947	5.8088889

Source	DF	Type I SS	Mean Square	F Value	Pr > F
LENGTH	1	25.56098453	25.56098453	4.12	0.0493
WIDTH	1	14.92976681	14.92976681	2.41	0.1290
STRUCT	1	48.91513114	48.91513114	7.89	0.0078
RL	1	25.43239049	25.43239049	4.10	0.0499
ESALEVEL	1	9.62480080	9.62480080	1.55	0.2204
ESALINCR	1	436.44842669	436.44842669	70.41	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LENGTH	1	0.95591406	0.95591406	0.15	0.6967
WIDTH	1	0.72201956	0.72201956	0.12	0.7348
STRUCT	1	5.77327243	5.77327243	0.93	0.3406
RL	1	24.44471139	24.44471139	3.94	0.0543
ESALEVEL	1	0.01061890	0.01061890	0.00	0.9672
ESALINCR	1	436.44842669	436.44842669	70.41	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	3.322666127	1.82	0.0770	1.82775930
LENGTH	-0.420244432	-0.39	0.6967	1.07017814
WIDTH	-0.017223163	-0.34	0.7348	0.05046636
STRUCT	-1.136916274	-0.97	0.3406	1.17809683
RL	0.044078103	1.99	0.0543	0.02219698
ESALEVEL	0.014201884	0.04	0.9672	0.34313879
ESALINCR	0.451673982	8.39	0.0001	0.05382972

1The SAS System

General Linear Models Procedure

Number of observations in data set = 45

1The SAS System

General Linear Models Procedure

Dependent Variable: COSTINCR

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	558.72581643	186.24193881	32.12	0.0001
Error	41	237.75062801	5.79879581		
Corrected Total	44	796.47644444			

R-Square	C.V.	Root MSE	COSTINCR Mean
0.701497	41.45490	2.4080689	5.8088889

Source	DF	Type I SS	Mean Square	F Value	Pr > F
RL	1	19.44273318	19.44273318	3.35	0.0744
STRUCT	1	49.37631579	49.37631579	8.51	0.0057
ESALINCR	1	489.90676747	489.90676747	84.48	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
RL	1	25.40332274	25.40332274	4.38	0.0426
STRUCT	1	24.79606182	24.79606182	4.28	0.0450
ESALINCR	1	489.90676747	489.90676747	84.48	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	3.259775104	1.92	0.0614	1.69471854
RL	0.044426013	2.09	0.0426	0.02122565
STRUCT	-1.517703832	-2.07	0.0450	0.73394680
ESALINCR	0.459531139	9.19	0.0001	0.04999506

```
1The SAS System
         Plot of COSTINCR*ESALINCR.  Symbol used is '$'.

COSTINCR |
      20 +
         |                                                $
         |
         |                                        $
         |                                              $
         |                                        $
         |            $       $                 $
      10 +        $     $
         |                 $    $
         |            $ $
         |        $   $$    $                     $
         |      $ $   $       $
         |      $$$$ $ $      $
         |     $ $$
       0 +     $$$ $
         ---+------------+------------+------------+------------+---
            0           10           20           30           40

                                 ESALINCR

NOTE: 9 obs hidden.
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