DOE/IR

June 1985

DOE/IR/05106--T91

DE89 013856

ANALYSIS OF MUNICIPAL BUS OPERATIONS FOR THE ADVANCEMENT OF FUEL CELL TECHNOLOGY

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Energy Task Force of the
Urban Consortium for
Technology Initiatives

Albuquerque, New Mexico
Environmental Health and Energy Department
Energy Management Division

MASTER

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PREFACE

The Urban Consortium for Technology Initiatives was formed to pursue technological solutions to pressing urban problems. The Urban Consortium conducts its work program under the guidance of Task Forces structured according to the functions and concerns of local governments. The Energy Task Force, with a membership of municipal managers and technical professionals from nineteen Consortium jurisdictions, has sponsored over ninety energy management and technology projects in thirty-two Consortium member jurisdictions since 1978.

To develop in-house energy expertise, individual projects sponsored by the Task Force are managed and conducted by the staff of participating city and county governments. Projects with similar subjects are organized into "units" of four to five projects each, with each unit managed by a selected Task Force member. A description of the units and projects included in the Fifth Year (1983-1984) Energy Task Force Program follows:

UNIT -- MUNICIPAL OPERATIONS

Energy used to support public facilities and services by the nation's local governments in 1983 totaled approximately 1.4 quadrillion BTU's. By focusing on applied research to improve energy efficiency in municipal operations, the Energy Task Force helps reduce operating costs without increasing tax burdens on residents and commercial establishments. This Fifth Year unit consisted of five projects:

- Albuquerque, New Mexico - "Analysis of Municipal Bus Operations for the Advancement of Fuel Cell Technology"
- Baltimore, Maryland - "The Hydrate Process for Sewage Sludge Dewatering: Commercialization Assessment"
- Memphis, Tennessee - "Application of Mini-van Technology to Van Pool Services"
- Phoenix, Arizona - "Capacity Optimization of Hydronic Flows: Energy Savings in HVAC Systems"
- Washington, DC - "Facilities Energy Monitoring System: Application in a Large Municipal Government"

UNIT -- MUNICIPAL AND COMMUNITY ENERGY MANAGEMENT

Of the nation's estimated population of 232 million, approximately 60 percent reside or work in urbanized areas. The 543 cities and counties that contain populations greater than 100,000 consumed a total of 49 quadrillion BTU's in 1983. Applied research sponsored by the Energy Task Force helps improve the economic vitality of this urban community by aiding energy efficiency and reducing energy costs for public services and the community as a whole. This Fifth Year unit consisted of five projects:

- Boston, Massachusetts - "Computer-based Preventive Maintenance"
- Cleveland, Ohio - "Coordinating Preventive Maintenance with Energy Management"
- Columbus, Ohio - "Budgetary Incentives for Municipal Energy Management"

- Denver, Colorado - "Municipal Recycling Programs: Potential for Waste Management and Energy Savings"
- Philadelphia, Pennsylvania - "Energy Assistance Program Information System (EAPIS): Coordinating Residential Assistance Programs"

UNIT -- ALTERNATE/INTEGRATED SYSTEMS

Effective use of advanced energy technology and integrated energy systems in urban areas could save from 4 to 8 quadrillion BTU's during the next two decades. Urban governments can aid the realization of these savings and improve capabilities for the use of alternative energy resources by serving as test beds for the practical application of new and integrated technologies. This Fifth Year unit consisted of five projects:

- Chicago, Illinois - "Implementation Methods for an Integrated Energy System"
- Houston, Texas - "Pricing, Regulation and Competition in Cogeneration: A Method for Comprehensive Risk Analysis"
- New York, New York - "Feasibility of Water-based District Heating and Cooling"
- San Antonio, Texas - "Central Energy Systems Application to Economic Development"
- San Francisco, California - "On-site Cogeneration for Office Buildings"

UNIT -- PUBLIC/PRIVATE FINACING AND IMPLEMENTATION

City and county governments often have difficulty in carrying out otherwise sound energy efficiency or alternative energy projects due to constraints in the acquisition of initial investment capital. Many of these investment constraints can be overcome by providing means for private sector participation in innovative financing and financial management strategies. This Fifth Year unit consisted of five projects:

- Hennepin County, Minnesota - "Shared Savings in the Residential Market: Financing Single Family Energy Conservation"
- Kansas City, Missouri - "Street Light Inventory and Maintenance System"
- Pittsburgh, Pennsylvania - "Shared Savings for Energy Conservation: A Model Process for Local Governmets"
- Saint Louis, Missouri - "A Development Strategy for Superinsulated Housing"
- San Diego County, California - "Innovative Financing for a Privately Owned Waste-to-Energy Facility"

Reports from each of these projects are specifically designed to aid the transfer of proven experience to other local governments. Readers interested in obtaining any of these reports or further information about the Energy Task Force and the Urban Consortium should contact:

Energy Program
Public Technology, Inc.
1301 Pennsylvania Avenue, NW
Washington, DC 20004

ACKNOWLEDGEMENTS

This project was conducted by the Energy Management Division of the Environmental Health and Energy Department in conjunction with Los Alamos National Laboratory (LANL). Los Alamos is a national research laboratory operated by the University of California for the U.S. Department of Energy.

The Energy Management Division expresses appreciation to Mayor Harry E. Kinney, Chief Administrative Officer, Frank A. Kleinhenz,(also an Energy Task Force member), and the Albuquerque City Council, for their support of Albuquerque's municipal energy management program.

The City of Albuquerque also acknowledges the initial coordination efforts of General Ernest Hardin, Assistant to the Manager, U.S. Department of Energy, Albuquerque Operations; and Jack Daly, President, United Energy and Minerals Corp., and Consultant to the Urban Consortium Energy Task Force.

Finanical support for this project was provided by the Urban Consortium Energy Task Force through a grant from the U.S. Department of Energy.

Rich Zelinski from Public Technology, Inc. provided extensive editorial assistance, as did Anthony Laska, Ph.D., unit manager from the City of New Orleans. Both gave the project staff general assistance throughout the course of the study.

Glenn Coontz, Energy Division Manager, served as the project director and was ultimately responsible for the timely completion of this study. He also provided editorial review of the final report. Mike Minturn, Assistant Energy Manager, was the project manager, overseeing the day-to-day operations. He is the author of this report.

A special note of gratitude to the following organizations and personnel who helped complete this study:

CITY OF ALBUQUERQUE

Environmental Health and Energy Department

Larry J. Gordon, Director, for direction and support of the Energy Management Division and its objectives.

Energy Management Division

Terry Pierce, Program Operations Analyst, for developing methodologies for the "roll-down" tests and "duty cycle" data collection.

Angelita Gamez, Program Operations Analyst, for perserverance with the tedious task of collecting bus "duty cycle" data with the computerized data logging equipment.

Julie Montoya, Secretary, for typing and correcting this report on the word processor.

Transit Department

Gary Garlick, Director, for cooperative spirit and guidance regarding Sun-Tran's management operation.

Lucas Montoya, Assistant Director, for sharing vast knowledge of Sun-Tran's maintenance system.

Jim Merrill, Associate Planner, for computer programs that greatly reduced the time required to manipulate data from the "roll-down" tests and "duty cycle" phases.

Fleet Management Division

Jim Morrisroe, Information Systems Manager, for devoting personnel to develop methods of obtaining Sun-Tran maintenance data.

Rick Handrich, Information Systems Staff member, for computer programs that sorted the voluminous maintenance data into a useful and summarized format.

Department of Finance and Management

Perry Baird and Leo Carabajal, Management Analysts, for assistance with budget preparation and analysis.

Boleslo Baca, Accountant, for preparation of fiscal reports to the City of Chicago.

GREINER ENGINEERING

Don Swick, P.E., and Rick Labato, Engineering Technicians, for swift and accurate production of additional data on the GMC RTS II bus.

LOS ALAMOS NATIONAL LABORATORIES

Alternative Energy Sources

Michael E. Berger, Deputy Associate Director, for initial guidance at the beginning of the project.

Energy Security Programs

Gerald Maestas, Program Manager, for initial guidance at the beginning of the project.

Electronics Division

Pete Murray, Electrical Engineer, for training city staff how to best proceed with the collection and analysis of bus system data, and for his guidance and support throughout the project.

Modeling and Economic Analysis Group

Fred Roach, Economist, for developing the economic baseline information for future comparison with fuel cell buses.

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CHAPTER 1

Overview

ABSTRACT

For the past decade or more, local governments have been faced with the management challenge of containing fuel costs and meeting community air quality standards. Fuel cells, while a future application for municipal bus systems, have the potential to almost triple the current miles per gallon, eliminate dependence on petroleum fuel, and reduce the level of harmful emissions such as carbon monoxide in comparison to diesel equivalents. The principal by-products of the fuel cell process are water and carbon dioxide.

Several technological and economic advances, however, must be made before fuel cell power plants can be used on the typical municipal bus. Further, it is highly possible that fuel cell-powered buses, representing a radical departure in design and operational needs, will require a different set of skills for the bus maintenance worker. As a joint effort between the city of Albuquerque and the Los Alamos National Laboratory (LANL), this study is a beginning effort to accelerate the use of fuel cell technology in actual bus applications.

In recognition of the developing stage of fuel cell technology and its differences from conventional power plants, this study was designed as an initial step necessary to move fuel cell research for

buses from the theoretical stages to a more applied setting. The information produced by this project will be valuable to national fuel cell research for buses to verify existing knowledge and extrapolate with relative certainty the performance and operating costs of buses powered by fuel cells. The secondary benefit from this investigation has been the development of improved maintenance and operational data on Albuquerque's city bus system.

The methodologies and information produced by this study should be useful not only to the city of Albuquerque and LANL, but to other transit operators and fuel cell researchers. The data will be made available through both the Urban Consortium Energy Task Force, and the vast networking capabilities of LANL.

PROJECT PURPOSE

The general purpose of this project was to obtain actual operating data on a municipal bus system for fuel cell power plant and propulsion system design, and to establish a first-order economic baseline for future comparison.

Research had three primary objectives:

1. To establish formal connections with the extensive expertise of a national laboratory and the actual operating experience of a municipal bus system;
2. To provide sufficient operational data useful in supporting a planned 10-year program to define standards and guidelines for fuel cell development; and
3. To develop improved maintenance data on the city's bus fleet to enhance current operations.

One of the goals of the Urban Consortium Energy Task Force is to initiate more rapport with the national laboratories, since local governments are prime candidates for test bed activities for new and improved energy technologies initiated by the labs. This project serves as an example of how technology transfer elements of the U.S. Department of Energy's mission can be met through the collaborative efforts of national laboratories and local governments.

LANL's current long term research plan concerning fuel cells for city buses calls for an effort of nearly ten years at a projected cost of $62 million. The expected result is an engineered and tested fuel cell propulsion system that is ready for production. For the short term LANL researchers need better bus data and feedback from transit operators on their objectives regarding drive cycles, fuel economy, and economics. The Albuquerque bus system study represents the first phase to generate this required information from real-world operations.

The information produced as a result of this project are of current utility to today's transit operators in terms of maintenance budgeting and scheduling. The methodologies used to obtain the data may also be useful to those bus system operators who wish to generate other information helpful in effective transit vehicle management.

REPORT ORGANIZATION

This report is organized and written to describe how bus system data was collected for LANL's fuel cell research program, to prescribe a preliminary fuel cell application for buses, and to summarize the successes, mistakes, and lessons learned during the study. The balance of the report is organized as follows:

Chapter 2 -- Background and Methodology

This chapter discusses the concept and management of the project, including descriptions of the roles played by the three primary agencies. The three agencies were the Energy Management Division and the Transit Department of the city of Albuquerque, and the Los Alamos National Laboratory. The original research design and fuel cell definition for 40-foot buses is also discussed.

Chapter 3 -- Project Description and Conduct

The results of the project are addressed in this chapter in terms of: 1) the technical and economic feasibility of using fuel cells on city buses now and in the future; 2) the standards and guidelines that are needed before fuel cells can be practical in mass transit applications; and 3) the present usefulness of the maintenance data produced by this project.

Chapter 4 -- Results and Lessons Learned

The lessons learned while conducting this project and the technical problems encountered during the course of the study are discussed in this final chapter along suggestions to aid the effectiveness of future working relationships between local governments and national laboratories.

Appendices

The five appendices to the report provide detailed information describing:

A. A summary of the engineering and design characteristics of the GMC RTS II bus and its auxiliary power requirements.

B. The methodology employed to create "roll-down" data points for use in a simulation of a fuel cell-powered bus.

C. Data collection methods to determine actual "duty cycle" operating conditions for use in a simulation of a fuel cell-powered bus.

D. A step-by-step listing of the computer program logic used in processing the "roll-down" and "duty cycle" data points.

CHAPTER 2

Background And Research Management

INTRODUCTION

Los Alamos National Laboratory (LANL) has been investigating for several years the vehicular application of fuel cells. This research program has centered around computer simulations of different vehicles on a variety of drive cycles, basic electrochemistry research to improve performance, applied research to reduce cost, and components and systems testing. As a result of preliminary research it appears that municipal buses are an appropriate initial vehicular application for fuel cell power plants for three primary reasons:

- The size of buses, particularly the typical 36-40 foot city bus, affords flexibility in packaging fuel cells.
- The use of a centralized municipal fueling and maintenance facility should aid the integration of a new system.
- The life-cycle costs associated with buses should improve the economics of a vehicular fuel cell application.

To better understand this rationale, it would be useful to describe the theory of a fuel cell power plant and its potential use in buses.

WHAT IS A FUEL CELL?[1]

The fuel cell is not a new power source. Fuel cells provided electricity for America's space program during long space voyages.

Simply, the fuel cell is a device that converts chemical energy directly to electrical energy.

Everyone is familiar with the dry-cell battery. Among other things, it powers the common flashlight. Electricity is produced by a chemical reaction within the cell itself. When the battery is "dead," it means the chemicals are used up.

Fuel cells operate in much the same manner: a chemical reaction produces the electricity. However, because chemicals are constantly introduced into a fuel cell from an external supply, the amount of stored energy does not depend on the cell's internal storage capacity. One common fuel cell uses hydrogen combined with oxygen from the air to generate electricity directly, leaving only pure water as a by-product (Fig. 1). Fuel cell efficiency is high. Actual fuel cells have been operated at efficiencies approaching 50%.

Of the two chemicals needed for fuel cell operation, only the hydrogen must be carried or produced on board the vehicle. The oxygen is readily available from the air. In the vehicle configuration being investigated at LANL, an organic fuel, such as methanol (methyl alcohol), is reformed catalytically to provide the hydrogen for the fuel cell. In this process (Fig. 2), a hydrogen/air fuel cell is used in conjunction with a steam reformer. The reformer allows the hydrogen to be carried in the form of a liquid fuel such as methyl alcohol (also known as wood alcohol or methanol). As hydrogen is required by the fuel cell, a mixture of methyl alcohol and water is passed over the hot catalytic bed of the reformer. Hydrogen and carbon dioxide gas are then produced, with the hydrogen used by the fuel cell to produce electricity for the electric motor.

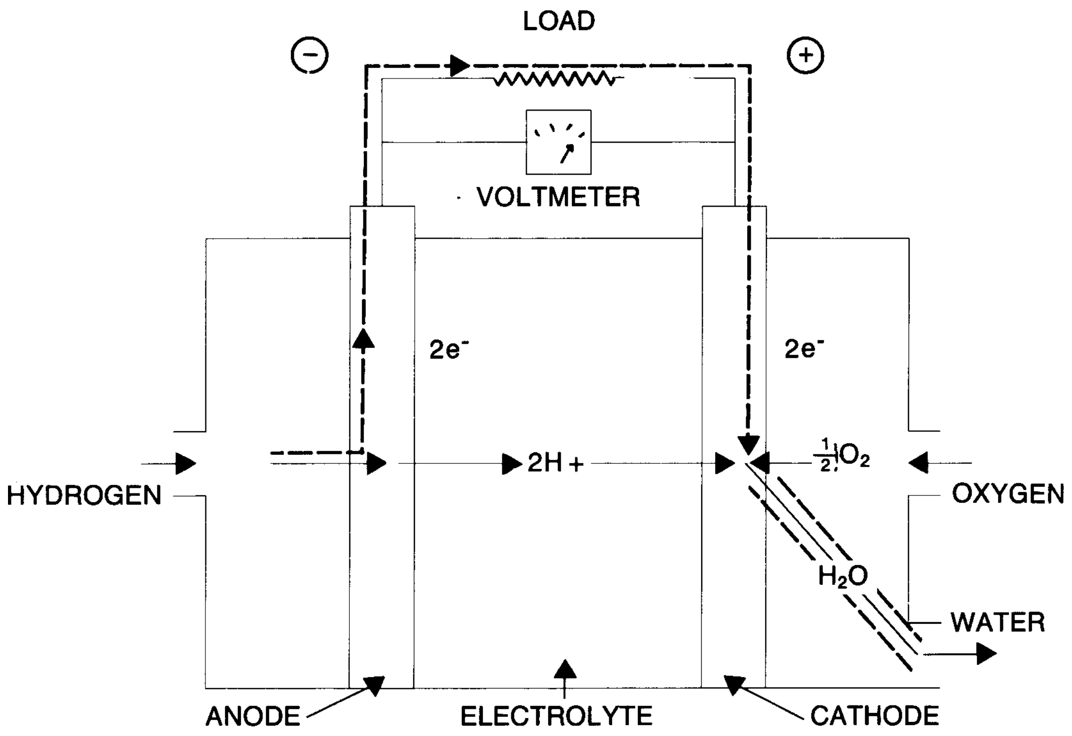


Fig. 1. Single cell schematic.

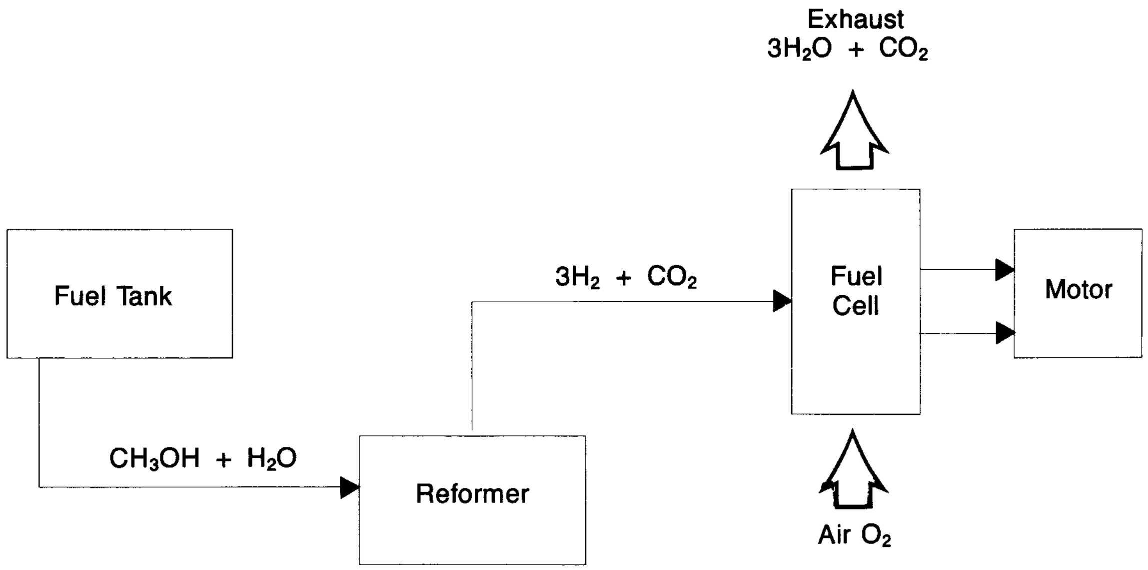


Fig. 2. Vehicle power plant block diagram.

The use of methanol as a fuel offers advantages. It is derived easily from coal, of which there is an abundance, and in the long term may be produced from organic waste, such as garbage. Methanol can be handled easily within the present gasoline fuel distribution system.

A fuel cell-powered electric vehicle, built according to today's technology, could do the following things.

- Obtain energy from nonpetroleum fuels stored on board and converted to electricity as needed.
- Be refueled in a few minutes, just as petroleum-powered vehicles are.
- Leave in its wake exhaust products of water and carbon dioxide (if methanol is the fuel) or water alone (if hydrogen is the fuel).
- Perform almost as well as a modern petroleum-powered vehicle.

The Battery

Even with advances in design, batteries still need recharging; recharging even the most modern battery takes 8 to 10 hours. At best, current electric automobiles have only a 100-mile range, followed by an 8-hour recharge period. Batteries simply cannot store enough energy on board to compete with the performance standards set by the internal-combustion engine.

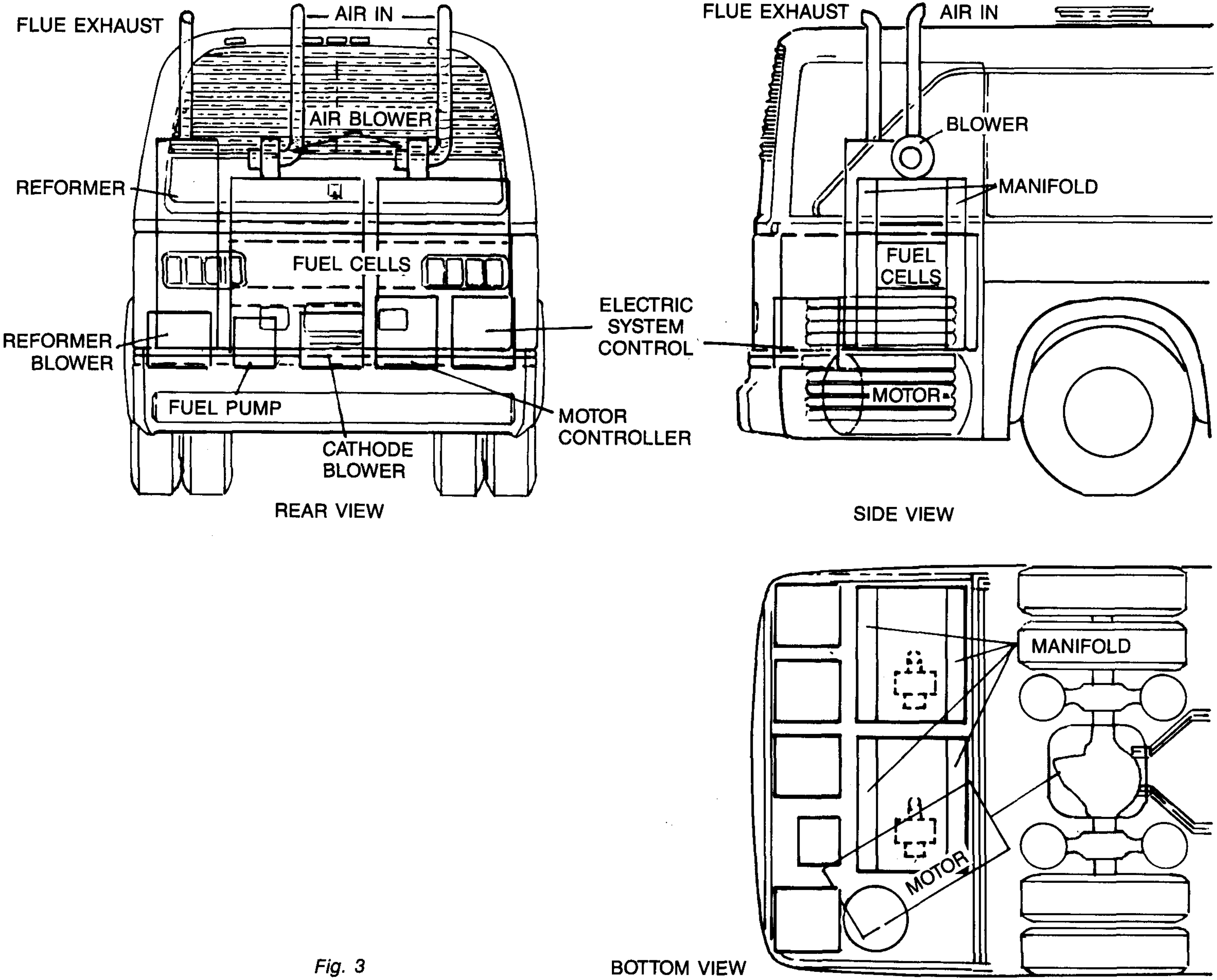
However, the battery is an excellent source of large amounts of quick energy. In an automobile quick energy--high power--is demanded only during acceleration and perhaps for hill climbing. Very little power is required to maintain cruising speed. As an example, a Volkswagen Rabbit will maintain a 55-miles-per-hour cruising speed using less than 15 horsepower, but it uses about 40 horsepower to reach cruising speed. Clearly, the full benefits derived from batteries are not always needed in an electric automobile.

Combining batteries with a fuel cell will give us a power source compatible with today's vehicle needs. The fuel cell can power the vehicle during cruise conditions, and the batteries can supplement the fuel cell during acceleration or hill climbing. The fuel cell also can recharge the batteries when power demand is low.

Advantages for Vehicular Applications

Low pollution and high efficiencies make fuel cells attractive in the transportation industry. As stated earlier, the primary by-products from a fuel cell are non-polluting water and carbon dioxide. Efficiency varies depending on the kind of fuel cell system; however, more useful energy can be extracted from fuel with fuel cells than with any other energy conversion device. Actual operating efficiencies range from 45% to 55%.

The method by which conventional diesel engines and fuel cells provide mechanical and electrical power are quite different. The diesel engine converts a fossil fuel to mechanical energy by means of a heat engine. For a diesel engine, the electrical requirements are met by converting mechanical energy with the use of a generator to electrical energy. The fuel cell avoids the intermediate conversion of a heat engine and converts a fuel directly into electrical energy. The vehicle is driven by an electric motor, thereby eliminating harmful emissions, the use of petroleum-derived fuels, and noise. A general arrangement for a fuel cell mounted in a municipal bus is shown in Figure 3 on page 12.



REAR VIEW

SIDE VIEW

BOTTOM VIEW

Fig. 3

Constraints to Practical Applications

The successful application of fuel cell systems will depend on the progress that is made regarding economic and fuel availability problems. LANL researchers have found it difficult to obtain cost figures for fuel cell systems, and current estimates may be off by a factor of three.

The economic barriers could be eliminated with advancements in the technology that address the present constraints of weight, size, maintenance unfamiliarity, and the overall fuel cell system reliability. Improvements are needed with the catalysts, electrodes, and power regulator system. Improvement in the electrocatalysts would affect cost and performance; advancements in the electrode materials would affect the system lifetime, costs and weight; and better engineering would affect endurance, weight and volume.

The types of fuel cells being investigated at LANL today include those using phosphoric acid, a solid polymer, a super acid, and an alkaline as the electrocatalysts. The phosphoric acid type appears to have an advantage over the others at this point due to its performance characteristics.

The other aspects of fuel cell technology today are in need of additional research.

This study has served to reinforce LANL projections that a fuel cell system for a municipal bus would need to provide 120 kW nominal and 360 kW peak power. However, the technology's state-of-the-art dictates a 600 pound power plant that requires 12 cubic feet, which presents the questions of how best to distribute the weight, or is weight distribution necessary?

In addition, assuming fuel cell buses can enter the market place on a strictly economic basis, then the cost factor of fuel cell system maintenance arises. Until fuel cell buses are completely phased into operation, there will be a need for dual maintenance and fueling facilities and specially-trained individuals.

The question regarding fuel availability is concerned with the availability of methanol, the fuel-of-choice for fuel cell bus systems. Methanol, as mentioned previously, can be derived from coal, garbage, or wood, and LANL researchers believe it may be less expensive as its use increases.

These are issues that fuel cell research for buses must address before this particular form of mass transit is considered a practical application. As other bus systems and fuels become more expensive, however, fuel cells may become more attractive because they are more efficient and less polluting than internal combustion engines.

The following chapters will discuss the development of an economic baseline against which fuel cell buses can be measured, and the standards and guidelines to be used for future fuel cell bus research. The economic baseline sets out some preliminary costs "allowed" for fuel cell buses given certain operating parameters. Both the economic baseline information and standards and guidelines were produced using the data developed by this study.

DESIGN OF THE RESEARCH PROJECT

Experience at Los Alamos National Laboratories (LANL) with fuel cell system studies and tests suggests that development of a fuel cell-powered vehicle is not a simple matter of integrating existing components.[2] A thorough feasibility study assessing both technical and economic issues and a demonstration plan are an essential prerequisite to a potential fuel cell-powered transit bus application. Information needs defined by LANL that were addressed during this project included a complete set of actual bus system operating data covering:

- Bus route data representative of various factors such as routes involving captive ridership, the velocity of buses versus time, a good sampling of grades, etc.
- Bus performance data on fuel consumption, accessory/auxiliary power requirements, the torque of the wheel/main drive shaft, and the weight of the buses, including occupants.
- Bus maintenance data on parts and labor, scheduled and non-scheduled maintenance, brakes, transmission, lubrication, and main power plant.

This extensive data gathering effort was the primary responsibility of the city of Albuquerque, with a grant from the Urban Consortium Energy Task Force. LANL staff provided training to city personnel for data collection and formatting and produced an economic baseline report on operating costs for a 40-foot diesel powered bus for use in LANL's cost comparisons with hypothetical fuel cell-powered vehicles. The economic baseline discussion is part of Chapter 3.

Project Conduct and Management

This project was managed by the city's Energy Management Division (EMD) of the Environmental Health and Energy Department. The work was performed by the EMD staff with technical assistance provided by the city's Transit Department, which operates the Sun-Tran bus system.

Technical assistance regarding the collection of data, particularly bus performance and routing, was provided by LANL. The labs also produced the economic baseline data.

Project Team

The following is a brief description of the agencies involved with this project and the roles they played:

Energy Management Division. Albuquerque's energy program is primarily concerned with controlling the consumption of energy in the forms of electricity, natural gas, and petroleum products in the performance of municipal government operations. One of the Energy Management Division's (EMD) activities, which made it well-suited for this study, is the provision of technical and planning assistance to other city government agencies. The Transit Department received several ancillary benefits from this project which will be discussed in Chapter 4. As the lead city agency for the bus data study, the EMD had responsibility for overall project management, including establishing the research methodology, conducting the research, maintaining liaison with LANL, and preparing the final report.

Transit Department/Sun-Tran. The city's Transit Department operates the Sun-Tran bus system throughout Albuquerque on 30 routes. Sun-Tran currently operates 91 peak period buses from a total fleet of 107 vehicles. On an annual basis, Sun-Tran carries over five million passengers and provides approximately 3.5 million annual revenue miles of service. Considered representative of a well-managed bus system, the Transit Department's role in this project was to provide technical assistance in the form of selecting buses and sample routes, collecting maintenance data, determining methods of mounting electronic monitoring equipment, in the test bus and encoding data into a computer, and processing the data into the desired reported formats.

Los Alamos National Laboratory. Los Alamos National Laboratory, through its Electronics Division and the Modeling and Economic Analysis Group, is responsible for conducting research on vehicular applications of fuel cells. Representatives from the Electronics Division provided orientation and training sessions regarding fuel cell research in general, and how to obtain the required data to advance the research on bus applications. An economist from the Modeling and Economic Analysis Group assisted with the determination of maintenance information needed, and developed the economic baseline data shown in Chapter 3.

REFERENCES

1) Los Alamos National Laboratories. What is A Fuel Cell? Los Alamos, New Mexico: Public Information Office, (No date); and, Los Alamos National Laboratories (LANL-80-2). The Fuel Cell-Powered Automobile: A Nonpetroleum-Fueled Alternative, by Byron McCormick; Los Alamos, New Mexico: Public Information Office, February, 1980.

2) Discussion with Pete Murray, Electrical Engineer, Los Alamos National Laboratories, Los Alamos, N.M. Fall, 1984.

CHAPTER 3

Project Description And Conduct

INTRODUCTION

The bus data study involved tasks relating to bus performance, routing, and maintenance with this information used to conduct a computer simulation of a bus using a hypothetical fuel cell propulsion system for the purpose of establishing a preliminary, first-order economic baseline.

The methodologies employed for each of these tasks, and the data produced, are described in this chapter. The practical assumption was made that for the near term (five years) no major advances would occur in the design of 40-foot buses. Therefore, it was appropriate for this project to focus on the most recently purchased buses, the GMC RTS II fleet of 25 vehicles which were put into service in 1983. An engineering summary of this bus is provided in Appendix A.

PERFORMANCE AND ROUTING DATA

Collecting the necessary information for performance and routing involved similiar methods. Both employed the use of a computerized data-logger and printer to establish a series of data points for measuring the velocity of the bus versus time in relation to road forces and actual operating conditions. The information was collected and analyzed by employing tests called "roll-down" and "duty cycle."

The methods for these tests and the corresponding information produced by them are discussed as follows:

"Roll-Down Tests"

The requirements for simulation of a fuel cell powered transit vehicle include determination of the forces involved in propulsion of the vehicle. Aerodynamic drag and rolling resistance, the principle forces which retard a rolling vehicle, were calculated as a result of the "roll-down" or "coast-down" testing. These parameters are needed to compute wheel power requirements over a given "duty cycle."

The rolling resistance is a function of the weight of the vehicle, the friction between road and tires, the slope of the road, and the drag in the drive train and transmission. The aerodynamic drag of a vehicle as its moves through the surrounding air is influenced by the square of the velocity, which means these forces are more significant at higher speeds.

For the GMC RTS II buses, an electronic instrument measured the distance traveled and speed at five second intervals. Accelerations were calculated by a computer-assisted linear regression of speed changes using "best fit" procedures. The equations used in the regression are displayed in Appendix B. For each test run the bus was accelerated to a specified speed and then allowed to coast or "roll-down." Tests were run traveling in both east and west directions to compensate for the slope of the road (gravity effects) and for the wind direction.

Data was collected over a two-day period traveling in both the east and west directions. The results shown are a composite of data points for the "roll-down" or "coast-down" test. As shown in Figures 4 and 5 the rate of deceleration decreases as the velocity of the bus decreases. When the bus is subjected to maximum acceleration, "floor boarded," Figure 6 shows that the rate of acceleration decreases as the velocity increases.

The results of the test runs were used to determine the rolling resistance and aerodynamic drag coefficients for the GMC RTS II buses. The mathematical analysis methods utilized, problems encountered, plots of data points for the test runs and degree of accuracy are discussed in further detail in Appendix B.

"Duty Cycle Tests"

The "duty cycle" tests were conducted to determine the road force requirements and "duty cycle" operating conditions for use in the simulation of a fuel cell-powered transit bus. The tests involved measurement of speed, time and distance for the GMC RTS II buses under actual operating conditions.

The changing demands on the vehicle power plant due to loads, grades, acceleration, and duration is called its "duty cycle." Data collected included the number of passengers, the altitude at 250-foot intervals along the various routes, and the speed and distance actually traveled over given routes at five second intervals.

The three bus routes selected for this study include Route 90 - North Coors express, Route 3 - Louisiana-Central, and Route 13 - University-Comanche. These routes represent the widest range of operating conditions that are encountered by the Sun-Tran system.

Figure 4 — **ACCELERATION VS. VELOCITY FOR GMC RTSII** — First Day

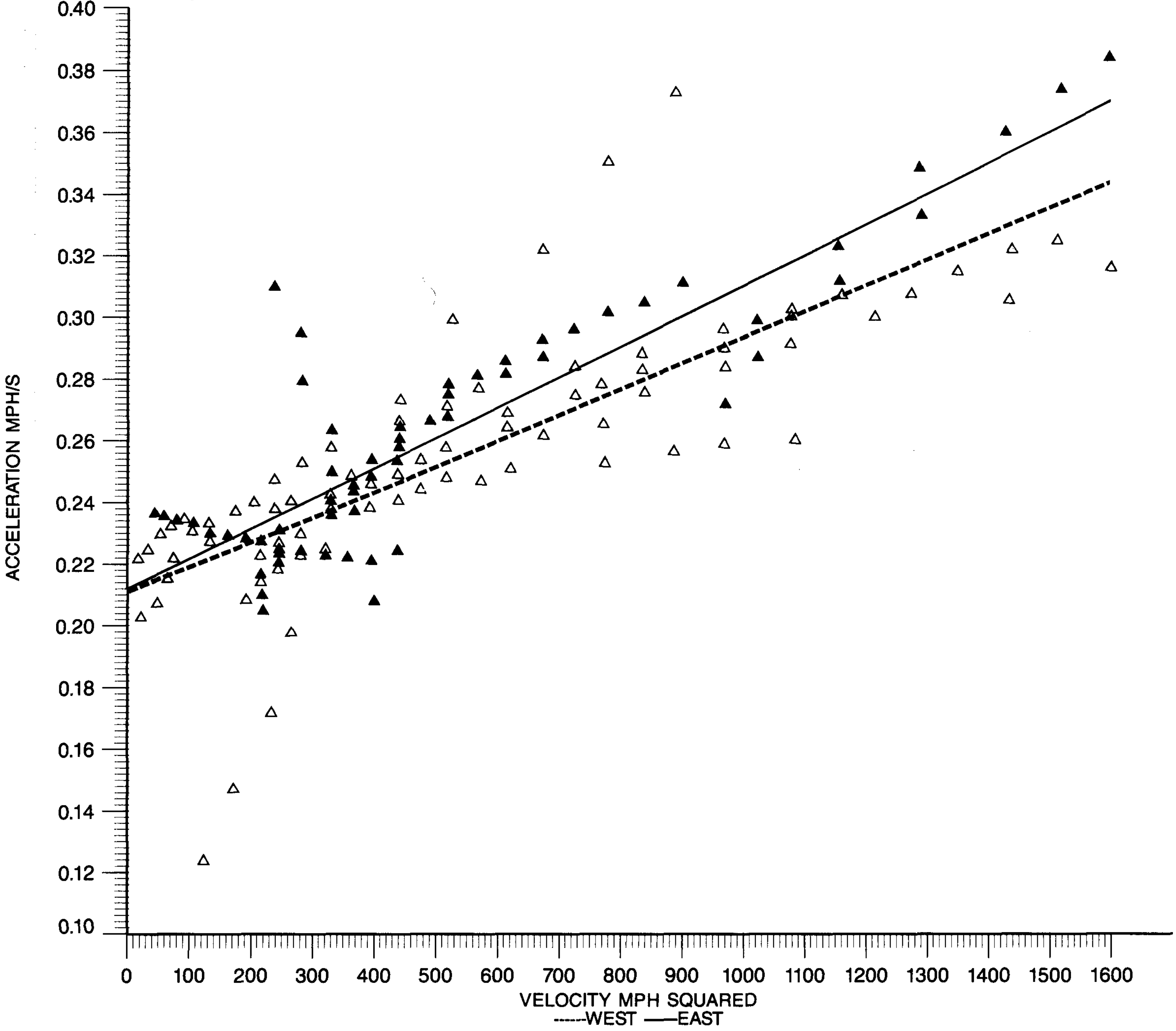


Figure 5 — **ACCELERATION VS. VELOCITY FOR GMC RTSII** — Both Days

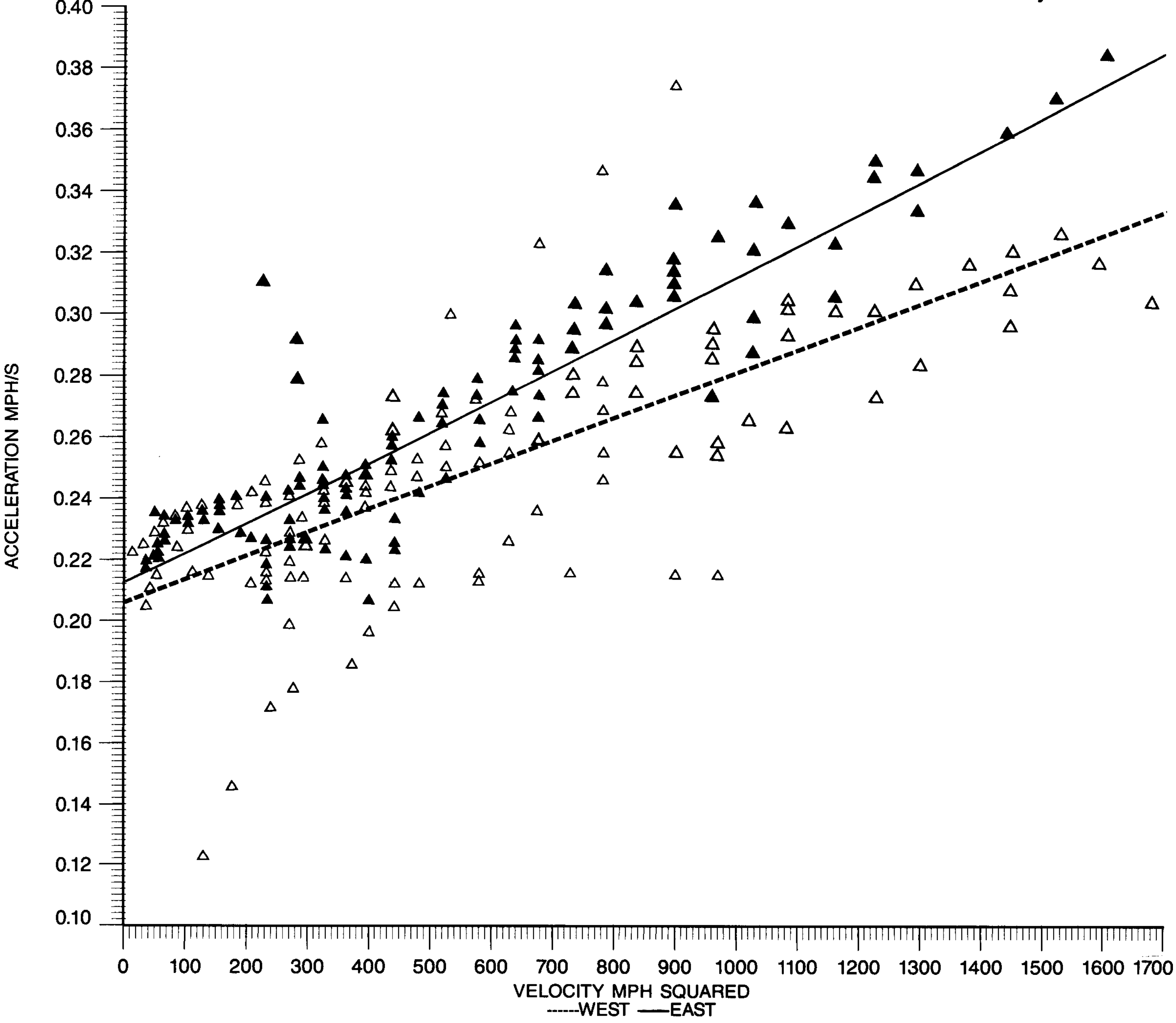
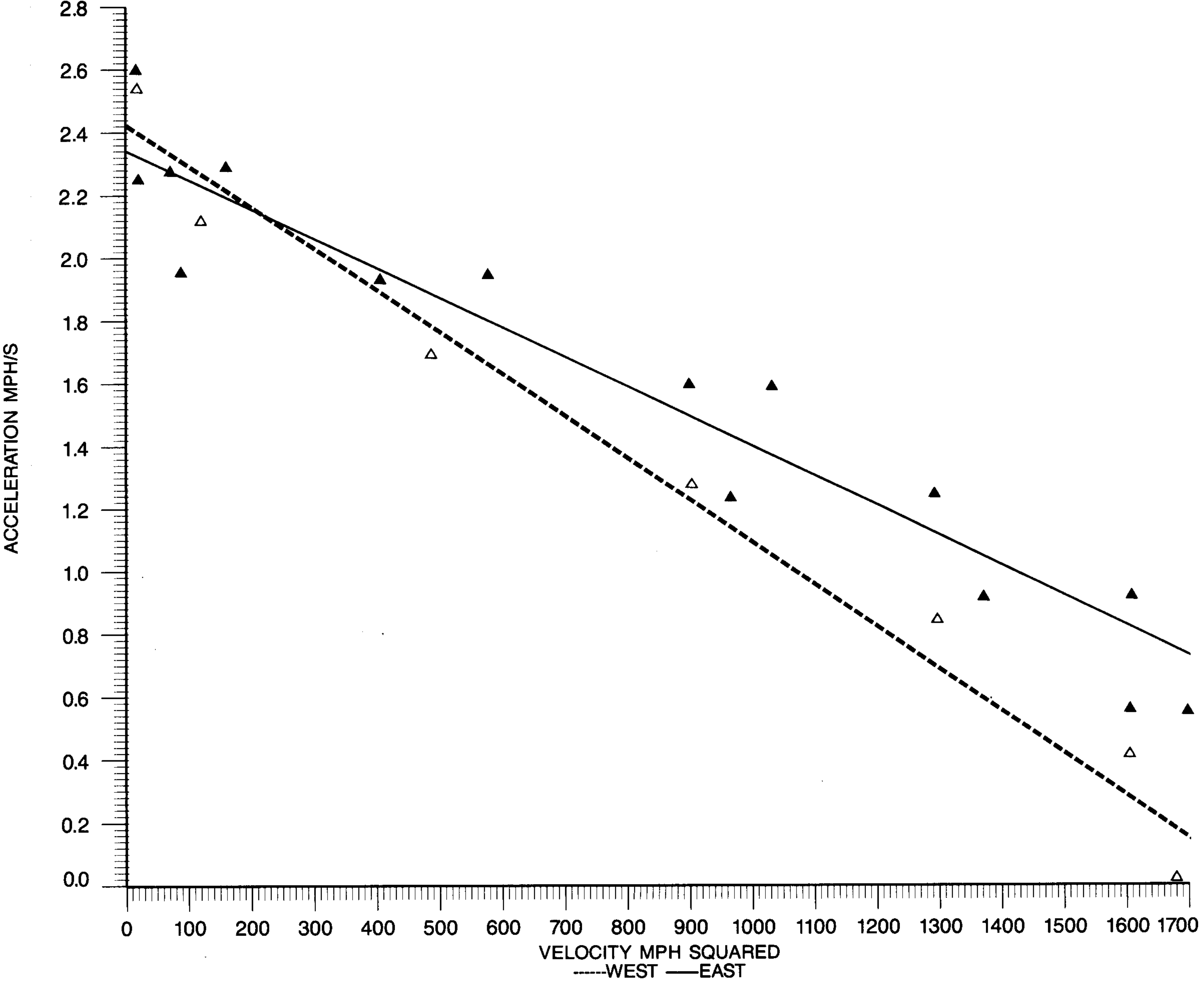


Figure 6 — **ACCELERATION VS. VELOCITY FOR GMC RTSII** — Maximum Acceleration



Route 90 is a high speed freeway-to-downtown commuter run of about 15 miles. Route 3 runs through some of the highest traffic density shopping center areas in Albuquerque with many stops and starts and high boarding and alighting (loading and unloading) volumes. Route 13 encounters altitude changes from 5000 feet to over 6500 feet in an eight mile grade.

Results of the "duty cycle" tests and a description of the methods used are given in Appendix C. Tabulated results for each "duty cycle" test include the stop name, time, measured distance, map distance, speed in miles per hour, slope (grade), the altitude, number of passengers on the bus, stop number, and reference stop number. An example output of "duty cycle" data for Route 3 is shown as Table 1 on the following page.

Maintenance Data

Crucial to the development of an economic baseline for fuel cell research are reliable maintenance data. This information consists of any repair work performed on the bus and the associated costs. To increase reliability, three fiscal years of data were produced.

This phase of the project involved: 1) creation of a computer program to extract maintenance information relating to the fleet of GMC RTS II buses; and 2) taking readings from the bus equipment relating to auxiliary power requirements; i.e., reading the rated electrical capacities of equipment such as, interior and exterior lights, air conditioning, etc.

TABLE 1: SAMPLE "DUTY CYCLE" DATA

DUTY CYCLE DATA, ALL VALID DATA MERGED WITH MAP DATA 17:51 WEDNESDAY, FEBRUARY 13, 1985
THE . INDICATES NO APPLICABLE CHANGE IN SLOPE
ROUTE 3, LOUISIANNA AND CENTRAL, OUTBOUND
ROUTE 90, CORRALES EXPRESS INBOUND
ROUTE 13, COMANCHE INBOUND

ROUTE	STOP NAME	HOUR	MIN	SEC	MEASURED DISTANCE	MAP DISTANCE	MPH	MAP SLOPE	MEASURED SLOPE	ALTITUDE	PATRONS ON BUS	STOP NUMBER	REFERENCE STOP NUMBER
3	CENTRAL	0	4	20	6408	6250	26	3.2	2.16802	5062	16	637	632
3	CEDAR	0	4	25	6593	6500	25	2.8	3.78378	5069	16	638	632
3	CEDAR	0	4	30	6779	6500	25	.	.	5069	16	638	632
3	SPRUCE	0	4	35	6963	6750	24	3.2	2.16216	5077	16	639	632
3	CENTRAL	0	4	40	7149	7000	24	2.8	3.76344	5084	16	640	632
3	SYCAMORE	0	4	45	7340	7250	24	3.2	4.18848	5092	16	641	632
3	SYCAMORE	0	4	50	7521	7250	23	.	.	5092	16	641	632
3	MAPLE	0	4	55	7700	7500	24	3.2	2.22222	5100	16	642	632
3	CENTRAL	0	5	0	7880	7750	24	3.2	4.44444	5108	16	643	632
3	CENTRAL	0	5	5	8057	7750	24	.	.	5108	16	643	632
3	ASH	0	5	10	8235	8000	23	3.2	2.25352	5116	16	644	632
3	CENTRAL	0	5	15	8410	8250	23	3.2	4.57143	5124	16	645	632
3	CENTRAL	0	5	20	8568	8250	20	.	.	5124	16	645	632
3	CENTRAL	0	5	25	8646	8250	7	.	.	5124	16	645	632
3	UNIVERSITY BLVD.	0	5	30	8651	8500	0	3.2	3.31950	5132	15	646	646
3	UNIVERSITY BLVD.	0	5	35	8654	8500	1	.	.	5132	15	646	646
3	UNIVERSITY BLVD.	0	5	40	8675	8500	3	.	.	5132	15	646	646
3	UNIVERSITY BLVD.	0	5	45	8697	8500	3	.	.	5132	15	646	646
3	UNIVERSITY BLVD.	0	5	50	8785	8500	15	.	.	5132	15	646	646
3	CENTRAL	0	5	55	8927	8750	21	2.4	2.17391	5138	15	647	646
3	MESA	0	6	0	9093	9000	22	3.2	4.81928	5146	15	648	646
3	TERRACE	0	6	5	9262	9250	22	3.2	4.73373	5154	15	649	646
3	TERRACE	0	6	10	9437	9250	24	.	.	5154	15	649	646
3	CENTRAL	0	6	15	9600	9500	21	2.0	1.47929	5159	15	650	646
3	BUENA VISTA	0	6	20	9700	9750	11	1.2	3.00000	5162	15	651	646
3	BUENA VISTA	0	6	25	9709	9750	0	.	.	5162	15	651	646
3	BUENA VISTA	0	6	30	9709	9750	0	.	.	5162	15	651	646
3	BUENA VISTA	0	6	35	9711	9750	1	.	.	5162	15	651	646
3	BUENA VISTA	0	6	40	9769	9750	10	.	.	5162	15	651	646
3	BUENA VISTA	0	6	45	9830	9750	6	.	.	5162	15	651	646
3	YALE	0	6	50	9832	10000	0	-0.4	-0.75758	5161	15	652	652
3	YALE	0	6	55	9832	10000	0	.	.	5161	15	652	652
3	YALE	0	7	0	9832	10000	0	.	.	5161	15	652	652
3	YALE	0	7	5	9832	10000	0	.	.	5161	15	652	652
3	YALE	0	7	10	9832	10000	0	.	.	5161	15	652	652
3	YALE	0	7	15	9890	10000	9	.	.	5161	15	652	652
3	YALE	0	7	20	10003	10000	17	.	.	5161	15	652	652
3	HARVARD	0	7	25	10129	10250	17	0.8	0.67340	5163	15	653	652
3	HARVARD	0	7	30	10221	10250	10	.	.	5163	15	653	652
3	HARVARD	0	7	35	10240	10250	0	.	.	5163	15	653	652
3	HARVARD	0	7	40	10273	10250	6	.	.	5163	15	653	652
3	CENTRAL	0	7	45	10384	10500	17	0.4	0.39216	5164	15	654	652
3	CENTRAL	0	7	50	10515	10500	18	.	.	5164	15	654	652
3	CORNELL	0	7	55	10655	10750	18	0.8	0.73801	5166	15	655	652
3	CORNELL	0	8	0	10805	10750	20	.	.	5166	15	655	652
3	STANFORD	0	8	5	10967	11000	22	0.8	0.64103	5168	15	656	652
3	STANFORD	0	8	10	11142	11250	23	1.2	1.71429	5171	15	657	652
3	STANFORD	0	8	15	11293	11250	19	.	.	5171	15	657	652
3	COLUMBIA	0	8	20	11349	11500	4	1.2	1.44928	5174	15	658	652
3	COLUMBIA	0	8	25	11349	11500	0	.	.	5174	14	658	658
3	COLUMBIA	0	8	30	11364	11500	2	.	.	5174	14	658	658

Twenty-three tables of data relating to repair costs, auxiliary power requirements, and fuel and oil costs were developed. Each of the twenty-three tables are not included in this report. Those interested in reviewing the other tables may obtain copies from the individuals listed on page 90.

There are nine divisions of repair code categories that were developed, each of which are described below:

Repair Code Descriptions

Division	Description
I. Clutch, transmission	Clutch rebuild, clutch adjust/repair, driveline (general), replace transmission, repair transmission, shifting mechanism.
II. Brakes	Brakes adjust/repair, brakes reline/replace.
III. Driven axle	Driven axles (general).
IV. Wheels/tires/suspension	Non-driven axle, wheels, tires, wheel bearings, suspension.
V. Engine	Engine repair, rebuild and/or repair engine, fuel system, air intake system.
VI. Ignition, battery	Battery, cranking system, charging system.
VII. Cooling system	Cooling system (general).
VIII. Preventative maintenance	3,000 mile APM 6,000 mile BPM 24,000 mile CPM
IX. All other items	Frame, glass, doors, seats, paint, exterior body, flooring instrumentation panel, lights (external), lights (internal), instruments/gauges. Air conditioning, heating and ventilation, route signs, destination signs, no defects found, towing special devices, cleaning accessories, radio equipment, emissions control, exhaust system.

TABLE 2: REPAIR COST BREAKDOWN - BY DIVISION
SUMMARY TABLE - FY 1984*

Repair Division	TOTALS			AVERAGE/BUS		
	MATERIAL	LABOR	TOTAL	MATERIAL	LABOR	TOTAL
I	651.06	290.78	941.76	65.11	20.76	52.32
II	22,829.01	24,536.58	47,365.59	913.16	981.46	1,894.62
III	7.41	34.89	42.30	3.71	8.72	10.53
IV	1,107.42	6,948.25	8,055.67	138.43	277.93	322.23
V	379.74	813.43	1,193.17	22.34	36.97	54.24
VI	5,056.45	1,592.91	6,649.36	1,011.29	63.72	265.97
VII	5,847.68	3,557.59	9,405.27	278.46	148.23	376.21
VIII	5608.84	26,233.03	31,841.87	224.35	1,049.32	1,273.67
IX	19,101.28	114,251.55	133,352.83	817.18	4,572.93	5,336.98
TOTALS			238,847.82			9,586.77

*Fiscal Year 1984 represents the only complete data available.

TABLE 3: AUXILIARY POWER REQUIREMENTS
MAXIMUM REQUIREMENTS

Item	HP	BTUH	KW
Heating	-	60,500	17.70
Cooling	-	66,200	19.40
Air Compressor	5	-	3.73
Lights	-	-	1.36
TOTAL			42.19

TABLE 4: AUXILIARY POWER REQUIREMENTS
ESTIMATED ANNUAL CONSUMPTION

Item	BTU/YR (x 1,000,000)	KWH (x 1,000)
Heating	25.8	7,555
Cooling	17.8	3,478
Air Compressor	-	3,879
Lights	-	382
TOTAL		15,294

TABLE 5: DIESEL FUEL CONSUMPTION & COST LIFE (FY83-85)

Bus No.	Consumption (Gallons)	Cost ($)	Miles Per Gallon
T801	14,331	13,230	3.93
T802	14,658	13,557	3.82
T803	15,628	14,388	3.58
T804	16,167	14,859	3.74
T805	11,834	10,928	3.76
T806	10,028	9,309	3.77
T807	16,420	15,208	3.82
T808	15,236	14,053	3.83
T809	15,927	14,618	3.30
T810	9,481	8,797	3.69
T811	11,373	10,497	3.65
T812	16,116	14,880	3.87
T813	11,479	10,491	3.06
T814	15,822	14,674	3.89
T815	15,820	14,548	3.92
T816	15,226	14,063	3.56
T817	14,652	13,462	3.92
T818	15,605	14,368	3.95
T819	14,892	13,877	3.81
T820	15,209	13,872	3.86
T821	11,247	10,401	3.66
T822	16,084	14,871	3.76
T823	16,124	14,940	3.93
T824	17,061	15,831	3.69
T825	15,907	14,730	3.88
TOTALS	362,327	334,452	
AVERAGE/BUS	14,493	13,378	3.75

TABLE 6: OIL CONSUMPTION & COST LIFE (FY83-85)

Bus No.	Consumption (Quarts)	Cost ($)	Miles Per Quart
T801	201	161	280
T802	199	159	282
T803	244	195	230
T804	192	153	315
T805	159	126	280
T806	97	78	390
T807	172	136	365
T808	188	149	310
T809	183	146	287
T810	89	71	393
T811	199	158	208
T812	208	166	300
T813	145	114	242
T814	175	139	352
T815	164	130	377
T816	140	112	388
T817	175	140	328
T818	173	138	356
T819	224	179	253
T820	194	151	302
T821	92	73	447
T822	239	190	253
T823	206	164	307
T824	208	165	302
T825	216	172	286
TOTALS	4,482	3,565	
AVERAGE/BUS	179.3	142.6	313.3

Economic Baseline Development

Life Cycle Cost Analysis

A preliminary analysis of the life cycle cost (LCC) of a city bus, powered by either the conventional diesel engine or a phosporic acid fuel cell, was conducted for the city of Albuquerque's GMC RTS II transit buses. The analysis was based upon the following set of economic and financial assumptions.

TABLE 7: LIFE-CYCLE COST FINANCIAL ASSUMPTIONS

Economic/Financial Parameter	Value
Period of Analysis	Late 1980's/Early 1990's
Life of Bus	15 Years
Financing Options	100% Debt (Bonds or Similar Instruments)
Debt Financing Period	15 Years
Interest Rate of Debt	10 %
Inflation Rate	5%
Taxes	None Applicable
Investment Tax Credits	None Applicable
Insurance Rate	6%
Depreciation Method	Sum of Digits
Depreciation Period	15 Years
(above two parameters do not affect net operating costs)	
Year Dollars	1985
Miles Per Year	50,000
Capital Cost Conventional Bus	$150,000
Salvage Value (10% of Capital)	$15,000
Fixed Operating and Maintenance (O&M) Cost	$0.53/mile
Fuel Use	3.72 mpg
Fuel Cost (Diesel)	$1.11/gal

The last seven parameters are allowed to change in the simple trade-off curves constructed in the actual LCC analysis (Figures 7-9)

Figure 7 portrays several curves, dollar capital cost (horizontal axis) vs. total operating cost per mile (vertical axis), for the conventional city bus. The horizontal line represents the cost for the "base case" parameter values listed above. That is, given the $150,000 cost of bus, the 3.72 mpg and $1.11 per gallon assumptions, and so on, the total operating cost per mile would be $2.85. If the fixed O&M costs are less than the assumed $1.44 per mile, then the $2.85 figure and all the curves plotted on the graph would be lower. However, the comparative positions of each curve would not change significantly.

Several pieces of information can be readily derived from the plots in Figure 7. First, because of the relatively high fixed cost component of operating and maintenance costs ($1.44 per mile but computed on a 50,000 mile basis), the total operating cost is significantly affected by changes to the revenue miles for a bus. An increase of 10,000 miles (20%) per year effectively lowers that component, as well as the capital cost per mile, and thus a total operating cost of about $2.40 per mile is realized (a 45¢ per mile reduction). On the other hand, lower revenue miles result in much higher total operating expenses; $3.50 per mile at 40,000 miles (a 20% decrease) and over $5.00 per mile at 30,000 miles (a 40% decrease). Scaling the fixed operating component somewhat to reflect potential changes in operating and maintenance procedures with lower mileage would lower those figures, but they would remain significantly higher than the "base case" 50,000 revenue miles assumed here.

Second, by lowering the variable component of operating and maintenance costs (operator expense and specific maintenance charges) the total operating expenses will of course decrease. Dropping the 53¢ per mile figure to 40¢ per mile (an approximate 25% decrease) lowers the total operating expense to $2.72 per mile (less than a 5% drop from the "base case" $2.85 per mile) at a $150,000 capital cost. A further 10¢ per mile decrease (from 40¢ per mile to 30¢ per mile) results in a total operating expense of $2.61 per mile: a 43% decrease in the variable O&M cost component results in only a 9% decrease in total operating costs. It is the variable cost component of most interest here for it includes salary to the operator and the routine maintenance required by the buses. If the fixed cost component is lower, then a corresponding drop in the variable component would result in a greater per cent change to total operating expenses, but there would still remain a large gap between the percentage drop in variable component and the resultant percentage drop in total costs. The fixed cost component includes plant costs, administration expenses, equipment costs, etc. Similar comparisons are made for increases to the variable component; at levels of 60, 70 and 80 cents per mile, respectively.

Third, changes in the price of fuel does of course change the total operating expenses. The dashed band brackets the capital cost/total operating costs trade-offs when 90¢ per gallon and $1.40 per gallon ($1.11 per gallon is "base case" figure) of diesel fuel prices are used in the LCC analysis. At 90¢ per gallon (a 19% drop) there is a corresponding decrease of only 7¢ per mile (a 2.5%

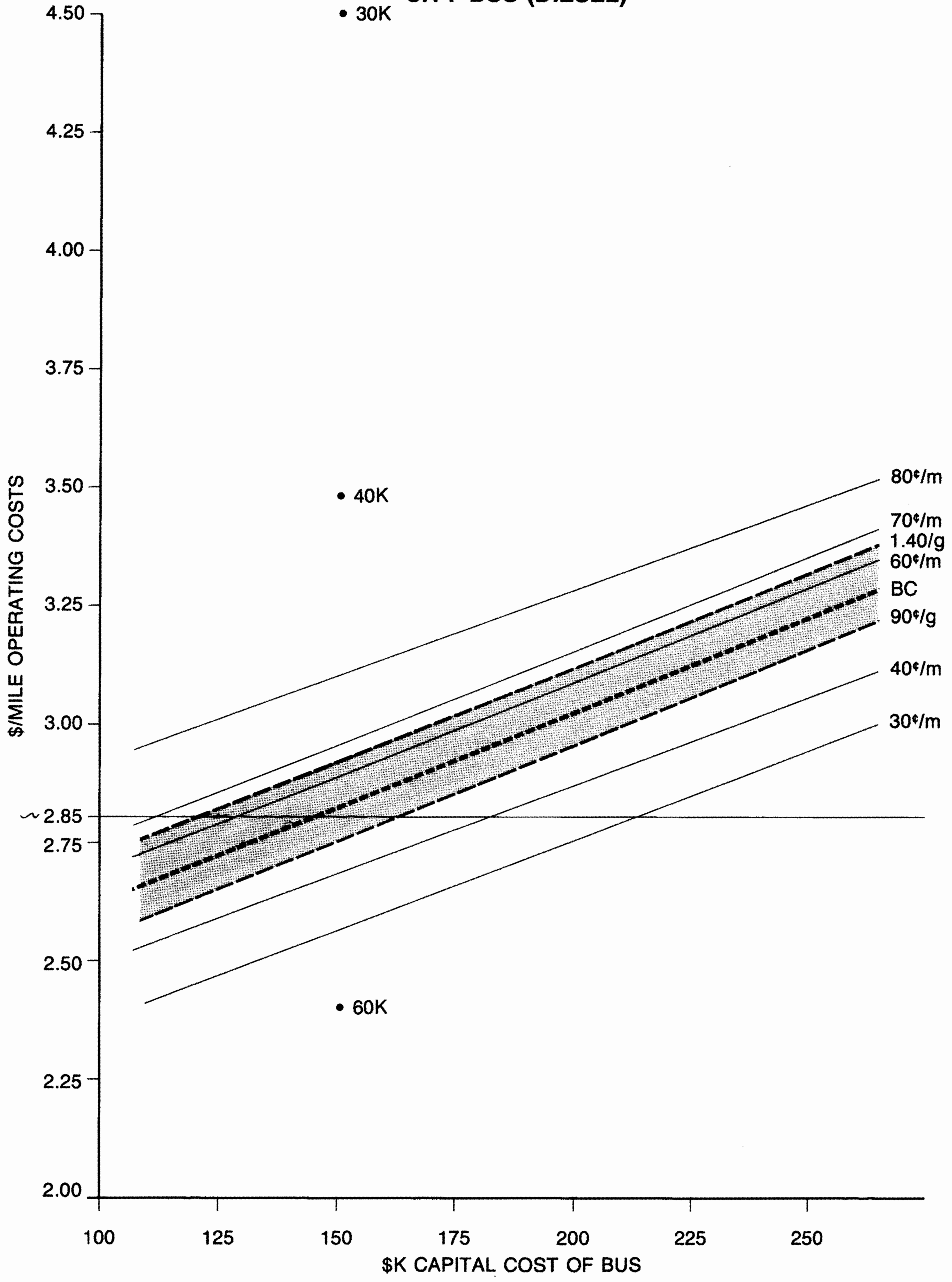
decrease) in the total operating costs. One could also interpret the 90¢ per gallon and $1.40 per gallon plots as increases and decreases in fuel efficiencies. For example, the 90¢ per gallon figure could represent a 19% increase in effective fuel efficiency (4.42 mpg vs. the 3.72 mpg) at the "base case" diesel price of $1.11 per gallon. Thus, the plots can be interpreted differently to reflect changes in other operating parameters.

The important items from this very simple and preliminary LCC look at conventional buses is the relative insensitivities of the total operating expenses to rather substantial changes in several key operating parameters (price of fuel, fuel efficiency, and the variable component of O&M expenditures). Of course, with other parameter assumptions, similar conclusions may not be as valid. The fuel cell powered bus is examined next.

Figure 8 portrays selected trade-offs between dollar capital cost and total operating cost for varying parameter assumptions for a fuel cell powered bus. The plot denoted by "3.73mpg" is equivalent to the diesel cell bus and results in the same cost vs. cost plot. That is, if fuel cell buses were priced equal to and had equivalent operating parameters and costs (such as fuel efficiency and O&M cost components) then for a $150,000 bus the total operating cost would be $2.85 per mile. However, we know that fuel cell-powered buses will not be priced the same nor have equivalent operating characteristics. Costs will be higher, but they will also be (partially) offset by higher fuel efficiencies and (possibly) lower O&M expenditures. To examine these potential parameter differences, several additional plots appear in Figure 8.

Figure 7

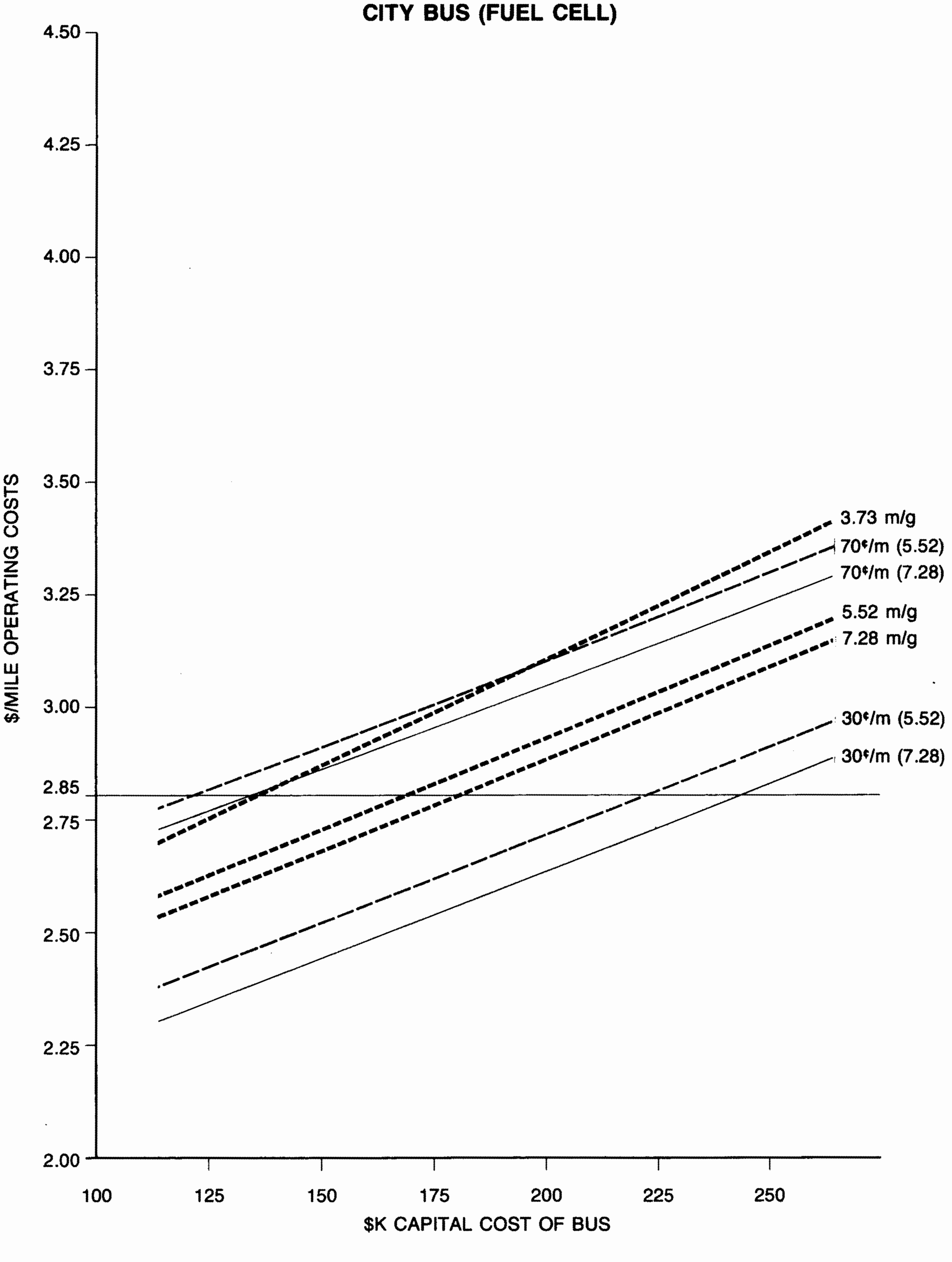
CITY BUS (DIESEL)



Fuel efficiency gains has been a strong point made for fuel cells. Recent estimates suggest that on a miles-per-gallon (diesel equivalent) basis fuel cell powered buses might approach 5.5 mpg in the near-term and more advanced technology 7.3 mpg. Methanol is the actual fuel assumed for analysis here with the price per gallon adjusted to reflect diesel equivalencies. Many argue that methanol may be less expensive as its use increases, but for purposes of the aggregate analysis presented here the price per gallon is assumed equivalent to diesel on a Btu delivered basis. Higher fuel efficiencies mean that higher capital costs are acceptable in maintaining a given level of total operating cost. For example, at the 5.52 mpg fuel efficiency a $2.85 per mile total operating cost translates into (allows) a captial cost of $175,000-$25,000 more than the comparable diesel-powered bus. Further fuel efficiency increases to 7.28 mpg allows for an additional $12 to $13,000 increase in the initial price of the bus and still maintain a $2.85 per mile total operating expenditure -- all other operating and cost assumptions remaining unchanged, of course.

Another strong argument that has been made in favor of fuel cell-powered buses is the potential for less maintenance costs. If maintenance expenditures are less on a per mile basis, then one would realize savings and thus could afford a higher initial captial cost. In Figure 8 both lower and higher variable O&M cost numbers are plotted given the higher fuel efficiency. If the variable O&M cost component could be dropped to 30¢ per mile (implying almost zero maintenance requirements, not likely and this is discussed below), then an initial investment of well over $200,000 could be acceptable under the $2.85 total operating cost level.

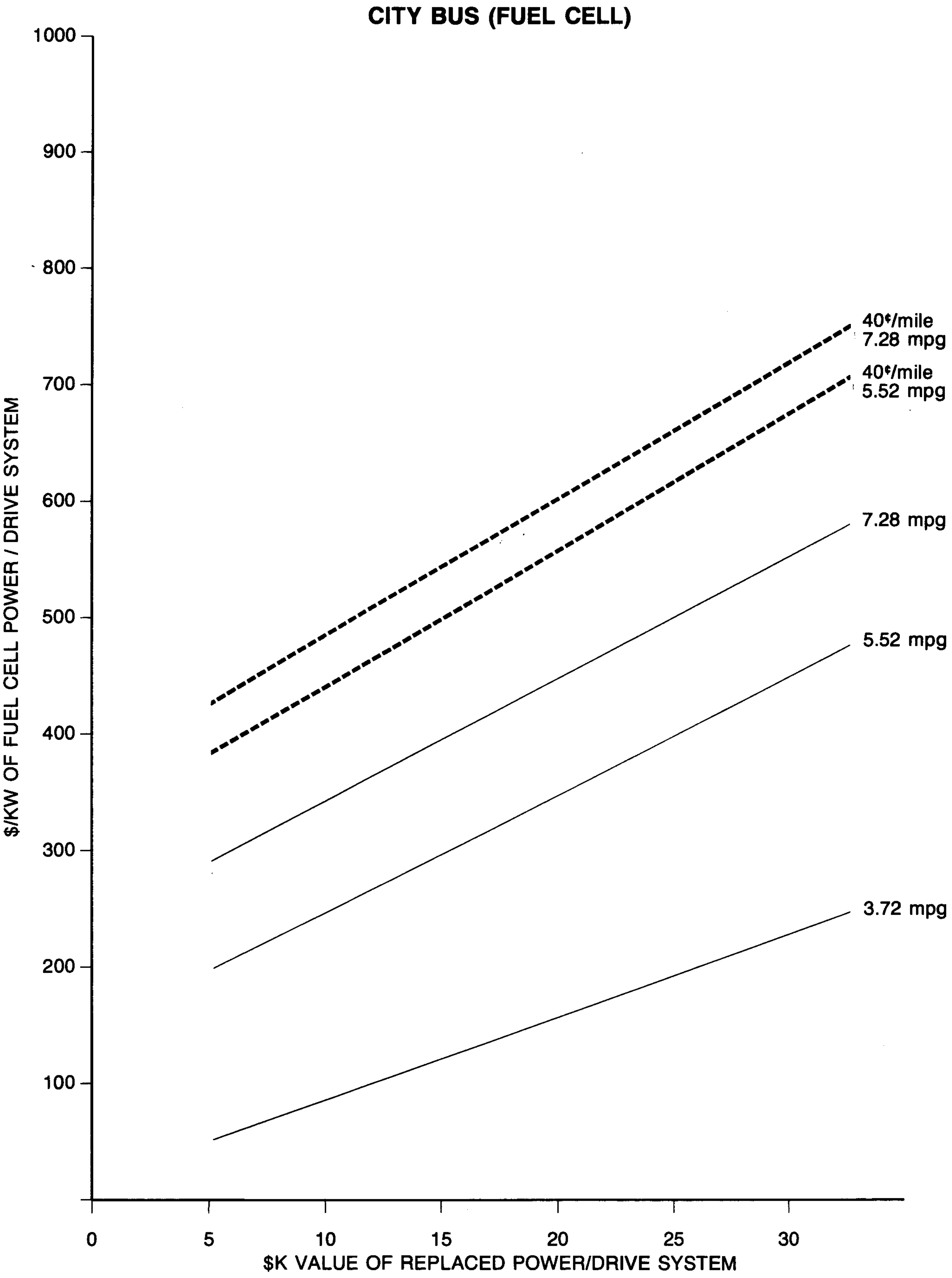
Figure 8


CITY BUS (FUEL CELL)
$/MILE OPERATING COSTS
4.50
4.25
4.00
3.75
3.50
3.25
3.00
2.85
2.75
2.50
2.25
2.00
100
125
150
175
200
225
250
$K CAPITAL COST OF BUS
3.73 m/g
70¢/m (5.52)
70¢/m (7.28)
5.52 m/g
7.28 m/g
30¢/m (5.52)
30¢/m (7.28)

Maintenance expenditures are only a part of the 52.6¢ per mile variable O&M cost component "base case" used in the analysis. The operator is also part of that component (realistically around half) leaving 30¢ per mile or less to be offset by O&M reductions. Further, a number of items make up the O&M variable cost component (see the preceding Maintenance Data section of this chapter). Over a three year period, the proportion of maintenance expenses attributable to the power train (engine, drive shaft, etc.) was less than 20%. Even considering brakes and a few other mechanical items (such as the A/C and heating systems) where some additional savings may be possible, the total O&M reduction might only approach 30% or so. Thirty per cent of a 30¢ per mile maintenance expense results in only a 9¢ per mile savings potential. In the next figure, a 10¢ per mile savings is plotted to examine the effect on capital cost allowances for fuel cells.

Figure 9 portrays costs a little differently than the previous two figures. Here the relationship between dollar value of capital replacement and allowed dollar value ($/kW) of a fuel cell system is contrasted. The replacement value is composed of two parts: the first is the diesel engine and associated drive train and the second is the incremental capital "allowed" for improvements to other operating expenses (such as fuel efficiency and lower maintenance costs) that may be attributable to a fuel cell power system. A 120 kW sized system has been suggested as a good potential for a typical city bus.

Figure 9


CITY BUS (FUEL CELL)
1000
900
800
700
600
500
400
300
200
100
$/KW OF FUEL CELL POWER / DRIVE SYSTEM
0
5
10
15
20
25
30
$K VALUE OF REPLACED POWER/DRIVE SYSTEM
40¢/mile
7.28 mpg
40¢/mile
5.52 mpg
7.28 mpg
5.52 mpg
3.72 mpg

If the fuel cell powered bus has equivalent operating characteristics and costs as the diesel-powered bus, then the fuel cell system must cost no more than the power system being replaced if total operating costs are to be maintained at the $2.85 per mile level. For example, if the value of the replaced diesel system was $15,000, then the "allowed" dollar cost of the fuel cell replacement would have to be less than $125 per kW (intersection of the vertical line from $15,000 replacement of the horizontal axis to the 3.72 mpg plot). However, if the power system on the conventional diesel bus was priced at $25,000 then the $/kW allowance increases to $200.

Given there are improvements to fuel efficiency, then "allowable" capital costs can be seen to increase substantially from the 5.52 and 7.28 mpg plot lines. Again, if the diesel system to be replaced is valued at $15,000 then the allowable fuel cell system cost increases to $310 per kW and $410 per kW, respectively, due to the now lower fuel operating costs. If additional O&M savings can be realized, then even higher $/kW costs can be accepted. The plots have been prepared such that once a pure replacement value of the diesel system has been determined, then the additional savings due to fuel efficiency and/or O&M expenses have been included in the plot themselves. Of course, those plots would be different under differing assumptions about the other operating characteristics and costs.

There are as of yet no good cost estimates of either the capital cost or O&M expenditures that may be associated with a viable fuel cell bus program. Therefore, the degree of real LCC analysis that can be performed is very limited. The $/kW figures derived from the above plots provide only first estimates of possible allowances. How these might compare to recent guesstimates on a turnkey bus operation is premature to say at this time. As more data becomes available it does provide a reasonable framework under which to carry out further assessments. It appears that total fuel cell power system costs will have to be less than \$600-\$700 per kW for such systems to be realistically considered good alternative candidates on cost considerations only, not withstanding the strongly supportive argument put forth by energy conservationists and environmentalists. Those arguments hold much merit but appear to have waned during the past several years. The energy conservation argument centers around replacement of imported oil (by methanol) more efficient use of energy in general, and use of our own indigenous resources (such as coal to methanol possibilities). The environmental position focuses on air pollution and noise abatement.

There are several other factors that must be considered when looking at LCC for a fuel cell-powered bus. Most will probably add to the costs during the transition years (diesel to fuel cell) and thus increase total operating costs and/or lower the "allowable" capital cost for the fuel cell buses themselves. Each factor is briefly discussed below and each focuses on the need for duplicate facilities and services.

Maintenance Shop -- Modifications, and possibly even additions, will have to be made to accommodate the fuel cell system. Both full support diesel and fuel cell plants must be maintained until such point as diesels are completely phased out. This dual maintenance plant and equipment capability will be more expensive than a single purpose facility. In addition, on a per square foot (or other appropriate measurement) bases the fuel cell facility may be more expensive than a comparable diesel facility.

Maintenance Tools -- A dual set (although many may support both programs) of maintenance tools will also have to be available during the transition year(s). Specialized tools for fuel cell maintenance may also be necessary further adding to these costs.

Service -- This particular component may be the most expensive for it will involve initial training for fuel cell repair which could be quite lengthy and extensive, as well as maintaining a service capability for diesel engines and the associated power/drive train. It is not clear whether the same individuals will be retained or new personnel should be recruited. In addition, other resources may be minimal in the community if buses are the only fuel cell powered vehicles operating on the streets.

Standards and Guidelines

One of the objectives of the study was to develop standards and guidelines for the development of fuel cell buses, based on bus data developed by the city of Albuquerque and current fuel cell research information produced by Los Alamos National Laboratories. The overall development program would involve ten research phases, beginning with a feasibility study, the nature of which is discussed in more detail in Chapter 4. The development program phases and the technical issues that must be addressed during the feasibility study are listed below:

Phase	Research
I.	Feasibility Study
II.	Component acquisition/development
III.	Component testing
IV.	Bench integration of an engineering model (prototype) fuel cell powerplant
V.	Bench testing under simulated loads with an engine dynamometer
VI.	Fuel cell powerplant integration into a test bus
VII.	Track testing
VIII.	Route testing
IX.	Incorporation of modifications dictated by the test program into the design of the powerplant and system
X.	Fuel cell bus production

The technical issues that must be addressed in the feasibility study include:

1. The drive cycle requirements for the proposed application including speed vs. time profiles, grade requirements, and operating time.
2. The torque and speed requirements imposed on the motor by the drive cycle.
3. The motors and controllers that are available on that could be built to best watch the drive cycle and powerplant requirements.
4. The efficiency, transient performance, lifetime, weight, volume, and packaging of current fuel cell technology.
5. The efficiency and transient performance of current fuel processor (reformer) technology.
6. The potential for on-board hydrogen storage to meet transient requirements.
7. Allowable charge and discharge cycles and lifetime of current battery technology.

8. Computer simulation of fuel cell or fuel cell/battery systems on the required drive cycle.
9. Evaluation of time out of service for recharging of batteries, fuel cell heat-up, and maintenance.
10. Identification of development requirements and limitations of specific hardware.
11. Estimates of real cost.

There are some technical design guidelines which have emerged from the study of simulated fuel cell buses using actual "duty cycle" data. Generally, the design of a fuel cell's power requirements for a vehicle differs from the approach used for other powerplants. The characteristic acceleration performance of an electric propulsion system, is that of a maximum torque (motor current) acceleration at zero and low speed. An internal combustion engine does not deliver maximum torque at zero speed, so the basic nature of the acceleration on a given drive schedule is different from that of an electric system. Because a fuel cell would be a power source in an electric drive train, it might appear that a characteristic electric acceleration would be called for. However, this would require the delivery of peak flow rates of fuel to the fuel cell almost instantaneously. (Fuel cell current is roughly proportional to fuel flow rate) This would be nearly impossible to accomplish when using decomposed methanol as the fuel. Originally it was thought that the stringent transient requirements on the fuel processor would make it impossible to use a fuel cell in anything other than a battery hybrid configuration with the fuel cell running at nearly instant power. It now seems as though considerable load following transient ability may be available from the fuel processor in view of performance characteristics which may be more nearly like those achievable in internal combustion engine powered buses. In the short term, however, a fuel cell battery hybrid system would be required to provide the necessary performance. This is due to the fact that fast response time methanol reformers are in a very early stage of development.

There are numerous uncertainties associated with the design of fuel cell powered buses, or with the design of any bus using a revolutionary power source. The initial thrust of the feasibility study is to determine what is required to meet the city bus performance needs. The guidelines for this will consist of the fuel cell powerplant nominal and peak powers. Normally, an internal combustion engine powerplant is sized for an application by determining the maximum power required for acceleration and gradeability specifications. A fuel cell power source offers the potential for providing a nominal, or continuous, power plus a peak, or short time power for acceleration. A fuel cell power source would then be sized much like an electric motor, with continuous, and peak ratings, for example one minute, or ten second ratings. It is essential that the nominal and peak power parameters are adequate for all phases of operation and for all conceivable bus "duty cycles." The "duty cycle" data gathered in this study is important to the development of these design guidelines. The approach is to use as much real "duty cycle" data as possible in order to develop general standards for fuel cell powerplants, rather than tying a design to a specific composite "duty cycle" and risking inadequacy of design for particular drive cycles. At the same time, it is important to avoid a "brute force" design in which the powerplant is sized so conservatively that weight and volume restrictions are far exceeded.

The feasibility study is discussed in Chapter 4 to highlight the initial technical, economical, and maintenance and operational questions that must be answered before a decision is made to continue fuel cell research for municipal buses. The discussion is couched in terms of guidelines which are clearly called for in the transit bus application, regardless of the choice of powerplant, namely, reliability, maintainability, safety, and so forth. The observations of the maintenance and operations in the Albuquerque bus system have served to emphasize the importance of these factors. Also, the question of maintenance and operational costs are quantified in this study as a guideline for comparison of future fuel cell systems. The specific costs will be a standard against which the ultimate success of advanced systems will be judged.

CHAPTER 4

Results And Lessons Learned

INTRODUCTION

The results of this investigation of a municipal bus operation are addressed here in terms of the feasibility of fuel cell buses and the lessons learned during the course of the research. The feasibility of fuel cell buses is organized to discuss the current economics and standards, the technical limitations and future research, and the utility of the developed maintenance data. For those transit operators who are considering similar studies of their bus systems for planning purposes, the lessons learned section (problems encountered) will highlight the technical aspects of conducting the study, the institutional arrangements for work with a national laboratory, and the workability of fuel cell technology on municipal buses.

FEASIBILITY OF FUEL CELL BUSES

Many technical and economic barriers will have to be eliminated before fuel cell buses can replace the conventional and diesel engine technology. The preliminary indication from computer simulations conducted by Los Alamos National Laboratory is that a fuel cell power plant for a 40-foot bus will need to provide 120 kW nominal and 360 kW peak power. Today's fuel cell technology dictates that the power plant would weigh 600 pounds and require 12 cubic feet of space; in other words, 1.7 pounds per kW. It is possible to construct a fuel cell bus; however, the technology's state-of-the-art is in its infancy, for vehicular applications, and no absolute statements regarding the feasibility of fuel cell buses can be made at this time. A fuel cell-powered bus holds much promise, but a mix of technological advances and changes in economic conditions will have to occur before municipal transit operators can afford to run them on city streets. The watchword is "cautious optimism." The following discusses the current limitations of the technology and what needs to occur before fuel cell buses can be considered a practical mode of municipal mass transportation.

Economics and Standards

The economic baseline of information developed by LANL represents a very early assessment of what kind of costs can be expected if a fuel cell bus were operating today under different operating conditions. It is reasonable to expect that it would cost $3.12 per mile to operate a fuel cell bus today (see figure 8), assuming a 5.52 mpg, an O&M cost of 53¢ per mile and a capital cost of $150,000.

However, as noted in Chapter 3, there are no reliable capital cost or O&M expenditure estimates associated with fuel cell buses. It does appear at this point, though, that if total fuel cell power system costs can be achieved for less than $600-700 per kW, the system can realistically be considered good alternatives in economic terms. The factors that would "allow" the higher bus capital costs are:

- an increased performance over the diesel engine bus, especially if the mpg diesel equivalent of fuel cells can increase from the 5.52-7.28 range.
- lower maintenance costs that may be attributable to a fuel cell bus.
- an increase in the cost of diesel fuel, or a lower cost for methanol on a BTU delivered basis. (The economic baseline information developed by LANL assumes an equivalent cost with diesel.)

While these considerations will make fuel cell buses more attractive to the transit operators, there are other factors that will add to the costs during a transition from diesel buses to fuel cell buses:

- Until diesel buses are phased out, there will be a need for a dual maintenance shop, and the fuel cell facility may be more expensive on a per square foot basis.
- A dual set of maintenance tools will also have to be available during the transition years.
- Servicing may be the most expensive because it involves training for fuel cell repair, and there will be in all likelihood a lack of resources in the community to support fuel cell power system maintenance.

The arguments tied to energy conservation and environmental improvement make a good case for fuel cell buses to replace diesel engines. These arguments have not been quantified here in terms of costs, but focus on qualitative aspects which many communities may hold in high regard:

- The use of fuel cell buses would replace imported oil since methanol is the fuel of choice; and fuel cells use energy more efficiently with our own indigenous resources. The example cited parenthetically in Chapter 3 is the use of coal in the production of methanol.
- The use of fuel cells would greatly reduce air pollution from buses since the only by-products are water and carbon dioxide.
- The use of fuel cells would reduce noise levels on the streets with the movement of tires on asphalt being the loudest sound from the bus.

In view of these economic and sociological factors, a fuel cell bus research program should continue to receive support from both the private and public sectors. The projected time for an introduction of this technology to the market place is 10 years, according to LANL. The next section will discuss the standards developed by LANL to address the technical limitations through additional research.

Technical Limitations and Future Research

The promising potential of fuel cell buses is their ability to increase performance, range, and efficiency, with a reduction of petroleum fuel consumption and harmful emissions. Today, methanol appears to be the fuel of choice by LANL researchers because it requires a low temperature for fuel processing, it allows the smallest fuel processing package, and it is expected to be thermally compatible with a fuel cell system. The electrolytes being considered for fuel cells are phosphoric acid, a solid polymer, a super acid, and an alkaline.

There are a number of unanswered questions surrounding the use of fuel cell buses, not the least of which is determining the "best type" of fuel cell system. LANL anticipates that further research over a ten year period is necessary to produce a commercially viable fuel cell propulsion system. This research program will address several elements.

Technical Aspects

LANL's current research activities are addressing the use of fuel cells operating alone or in concert with storage batteries acting as load levelers and as storage for energy recovery during braking. LANL expects to be investigating several fuel cell/power plant configurations, both as a pure fuel cell and as a hybrid power plant with a battery auxiliary. Technical aspects that will be addressed to define a practical fuel cell system include:

- Performance potential
- General size, weight and configuration
- Maintenance complexity
- Expected reliability of the components and the system
- Power density, system efficiency, and other performance measures
- Fuel and hardware capital and operating costs
- Electric propulsion controls

Operator Requirements

In addition, the "best" type of fuel cell/fuel catalyst combination must be analyzed in the context of the transit operator's requirements. These needs include:

- High vehicle reliability
- Ease of maintenance
- Vehicle and facility safety
- Low life cycle costs
- Low pollution levels
- Low noise levels
- Ability to perform on existing routes and on existing schedules
- Moderate acquisition costs for propulsion systems

It is expected that these future analyses will also identify new operational procedures that must be employed by bus operators to meet the requirements of fuel cell operation. Additional analyses are also needed on selected fuel cell power plants to determine the probable failure modes and the effect of such failures on vehicle safety and performance.

Engineering

If no system shows reasonable ability to meet these requirements, the use of fuel cells in buses must be judged infeasible in the near term. If further research indicates that these requirements can be met, then the concept must be proven in actual applications. This "proof of concept" phase of LANL's research program would identify:

- Modifications necessary to the present technology for bus power plants
- Performance ratings from a test track, or test bed, operation
- Major engineering issues

Cost Analyses

Cost analyses must then be performed to assess the life cycle costs for commercially viable fuel cell systems, considering:

- Vehicle capital costs
- Extra facility costs due to fuel cell usage
- Fuel and servicing costs
- Maintenance costs
- Spare costs
- Fuel costs
- Component and system useful lives
- Pollution control costs
- Need for public financial subsidy

Assuming the developed fuel cell bus passes both technical and financial tests, the expected result of this effort will be an engineered and tested fuel cell bus that is ready for production.

Utility of Maintenance Data

The maintenance data collected on the GMC RTS II buses serves two purposes. First, an economic baseline is now developed against which fuel cell bus systems can be measured by LANL in life-cycle cost analyses. Second, the maintenance information is at a level of detail, as shown in the tables of Chapter 3, that allows transit operation planners to more accurately project annual performance and costs associated with GMC RTS II buses.

The utility of the maintenance data to transit planners of Sun-Tran and other municipal bus systems deserves more explanation. The information from a sample size of 25 buses of recent vintage traveling an average of 50,000 miles annually across various grades and altitudes affords transit planners with a good basis from which to make sound operational and budgeting decisions. Transit operators using the GMC RTS II will find the data more useful than operators with other, older equipment.

The repair cost breakdown into nine divisions (Table 1 pg. 27) shows material and labor costs in terms of totals and averages per bus. The tables for diesel fuel and oil consumption and cost (Tables 4 and 5) for the 3 years of operation of the GMC RTS II fleet and listed, by bus, showing consumption, cost, and miles per gallon and quart, with a calculated average per bus.

These three tables of information can be of particular usefulness to Sun-Tran, and other transit operators with the GMC RTS II, for determining, for example, the percentage maintenance-of-effort operational costs attributable to this type of bus. In addition, by reviewing the costs associated with the nine repair divisions a clearer picture of specific material and labor costs can be developed. For example, clutch and transmission costs can be budgeted separately from ignition and battery repairs.

While this information is useful in arriving at figures for average costs of operation, the reader should remember that the average cost of providing a unit and service for a bus system of 25 vehicles, in this case, is not directly comparable to the same average cost calculated for fleets of different sizes or bus types.

LESSONS LEARNED

Major lessons learned from this project can be stated in terms of the performance, routing and maintenance data collection efforts as well as for the institutional relationships with LANL and other laboratories.

Performance

The research plan originally called for the collection of bus performance and routing data using a fifth wheel and data-logger as supplied by LANL. This arrangement failed to produce reliable information for two reasons:

- Fifth wheels are well suited for collecting information during test track operations where surfaces are smooth. They were not appropriate on bus routes where bumps and other road surface irregularities rendered the data useless because the wheel did not maintain constant surface contact.
- Although the "roll-down" tests were conducted on a smooth, recently surfaced airport runway, the fifth-wheel provided by LANL was originally used on a Volkswagen Beetle. Its mounting devices were incompatible with the GMC RTS II bus.

Therefore, transit operators who are considering similar bus system research projects are advised to use a mobile distance processor. This device measures revolutions of a tire by means of a proximity switch which measures equally spaced metal targets mounted around the wheel rim. The switch sends a pulse to an on-board microprocessor each time it is passed by a target. This is a more reliable method of collecting velocity, time, and distance data over irregular road surfaces than is the fifth wheel.

Routing

During the preparation and implementation of the second series of duty cycle data collection tests, certain problems and recommendations were developed. The quality of the signals from the sensor, which are generated by the metal targets mounted to the rim, is improved when the sensor and targets are properly adjusted. The metal targets were spot welded to the rim, and the sensor was mounted on a bracket which was adjustable in all directions.

If future tests were required, an adjustable mounting device for the targets would also be recommended. Problems with the actual recording device were encountered during cold ambient temperatures (before bus warmed up inside) and when bus was idling and interior lights were operating (inadequate power). If future tests were required, the location of data collection equipment and operator in seats on right hand side of bus (instead of behind driver) would improve collection accuracy and eliminate the need for multiple runs of the same route.

Maintenance

In the early stages of this study project personnel thought it would be a relatively simple matter to access the city's computerized Vehicle Information System (VIS) to obtain the needed maintenance information. However, the required data was encoded in such a way as to make retrieval difficult. Staff first thought the easiest way to provide LANL with the required maintenance data would be to spool the entire maintenance file onto a magnetic tape and let LANL select the information they needed. This was deemed too cumbersome because of computer incompatibility problems and time associated with manually reviewing large stacks of computer printouts.

The problem was resolved by having LANL provide project staff with a list of maintenance data needed and the desired format; a computer program was then developed to extract the required information.

This data collection phase involved more time than expected due to the relatively narrow nature of the information needed to enable LANL to run its computer simulation.

Institutional Arrangements

This project was financed by the Urban Consortium Energy Task Force to address a municipal energy research requirement organized and directed by city staff. The nature of the study put the city in a position similar to that of a sub-contractor to LANL. The city was providing an extensive service to LANL, although no contractual arrangements were made beyond a formal agreement in which no funds were to be exchanged. This type of agreement should be standard procedure for other municipalities conducting mutually beneficial research projects with national laboratories. To expedite similar projects, however, it may be wise to include a contract with payment for work conducted by the laboratories.

Both the city and LANL benefitted from this study. LANL scientists received a greater level of detail on a representative municipal bus operation that is vital to advance fuel cell system studies. Furthermore, the Albuquerque data included sufficient maintenance and operating cost information necessary for establishing a first-order economic baseline for future comparison with fuel cell buses. The city has benefitted first by having developed data that will be useful in terms of budgeting and planning purposes and, second, by receiving a thorough introduction into fuel cell technology for city buses.

A good working relationship has been established between the city of Albuquerque and Los Alamos National Laboratories to the extent that the city is hoping to participate in future phases of fuel cell bus development involving the laboratories.

APPENDIX A:

Engineering Summary Of The GMC RTS II Bus

GMC RTS II 800 SERIES BUS
GMC Truck & Coach Operation
General Motors Corporation
31 Judson Street
Pontiac, Michigan 48058

Contact: W.F. Mc. Queen, Coach Sales Administator
Truck & Bus Group
Phone: 313-456-3502

I. PHYSICAL INFORMATION

Length 40 feet

Height 10 feet

Width 102 inches

Weight 36,000 pounds (without passengers)

Passengers 46 (seated total)

Glass Area 372 Square Feet

Glass U-Factor 0.56 BTU/SQ.FT./DEG-F/HR

Glass Shading Coefficient 0.6

Wall/Roof Area: 708 Square Feet

Wall/Roof U-Factor 0.2 BTU/SQ.FT./DEG-F/HR

Floor Area: 288 Square Feet

Floor U-Factor 1.39 BTU/SQ.FT./DEG-F/HR

II. COOLING SYSTEM

Type: Reciprocating Compressors (r-12)

Manufacturer: TRANE

Design Load: 5.5 Tons (or 66,200 BTUH in Albuquerque, New Mexico)

III. HEATING SYSTEM

Type: Hot Water/Electric

Manufacturer: TRANE

Design Load: 60,500 BTUH (in Albuquerque, New Mexico)

IV. ELECTRICAL SYSTEM (Auxiliary Lighting)

Marker Lamp 3.2 Watt, .27 Amp, 12 Volt

Front Side Directional Signal 27 Watt, 2.1 Amp, 12 Volt

Side Marker 3.2 Watt, .27 Amp, 12 Volt

License Lamp 3.2 Watt, .27 Amp, 12 Volt

Back-Up Lamp 26 Watt, 2.1 Amp, 12 Volt

Speedometer Lamp 4 Watt, .17 Amp, 24 Volt

Driver Switch Panel 1.1 Watts, .08 Amp, 14 Volt

Evap. & Engine Compartment Lamp 14.5 Watt, .61 Amp, 24 Volt

Exit Door Lamp 4 Watt, .17 Amp, 12 Volt

Exit Door Signal Lamp 3.2 Watt, .27 Amp, 12 Volt

Indoor Flourscent Lamps 60 Watts, 12 Volt, 10 Fixtures

V. AUXILIARY ENERGY CONSUMPTION ESTIMATES

The major auxiliary energy consuming items for the Sun-Tran GMC RTS II 800 Series buses includes:

1. Heating System
2. Cooling System
3. Air Compressor
4. Lights

The heating and cooling systems function to provide a comfortable environment for the passengers. The air compressor is required for the brake system and the doors. The lights on the bus include interior and exterior lights which are normally used in early morning and late afternoon.

In order to determine the annual heating and cooling requirements, the overall heat transmission coefficient for the bus was determined.

WALL: R · Value

Inside Air Film = 0.5 (15 mph average speed)

Fiber Glass Panel = .21

Fiber Glass Insul. = 4

Outside Air Film = .17

Total "R" = 4.88

U = 1 R = .2

ROOF: R · Value

Inside Air Film = 0.5 (15 mph average speed)

Fiber Glass Panel(2) = .42

Fiber Glass Insul. = 4

Outside Air Film = .17

Total "R" = 5.09

U = 1 R = .2

FLOOR: R · Value

Inside Air Film = 0.5 (15 mph average speed)

Metal Floor = 0

Rubber Matting = .05

Outside Air Film = .17

Total "R" = .72

U = 1 R = 1.39

The annual energy requirements were based on the degree-day methods presented in Chapter 28 of the A.S.H.R.A.E Handbook of Fundamentals. The net overall heat transmission coefficient, UA value, was determined for both summer and winter. Using the TRACE load design program, which is based on current A.S.H.R.A.E algorithms, the design loads wre calculated. These design loads, which include internal heat gains and solar effects, were divided by the design temperature differences to determine UA (NET) for summer and winter.

The calculations below show the results of the energy consumption estimates.

1. HEATING

Q(HTG) = UA(NET) x F x HDD x 24 HR/DAY

Where:

Q(HTG) - Total heating requirements (BTU/YR)

UA(NET) - Overall winter heat transmission coefficient (BTU/HR/DEG-F)

F - Utilization factor, if H is the hours per week utilized, then: F = H/168

HDD - Heating degree-day value for Albuquerque, New Mexico 4292 (DEG-F/DAY/YR)

Therefore:

Q(HTG) = 1043 x .24 x 4292 x 24 HR
= 25.8 MMBTU/YR

Electrical Requirement:

25.8 MMBTU YR E 3413 BTU/KWH = 7.55 KWH/YR

NOTE: MMBTU = Million BTU = 1,000,000 BTU

2. COOLING

Q(CLG) = UA(NET) x F x CDD x 24 HR/DAY

Where:

Q(CLG) - Total cooling requirements (BTU/YR)

UA(NET) - Overall summer heat transmission coefficient (BTU/HR/DEG-F)

F - Utilization factor, if H is the hours per week utilized, then: F = H/168

CDD - Cooling degree-day value for Albuquerque, New Mexico 747 (DEG-F/DAY/YR)

Therefore:

Q(CLG) = 4138 x .24 x 747 x 24½HR

= 17.8 MMBTU/YR

Electrical Requirement:

MMBTU/YR E 3413 BTU/KWH E 1.5COP = 3478 KWH/YR

3. AIR COMPRESSOR

AC(KWH) = KW x DX x HOURS x 52 WEEKS/YEAR

Where:

AC(KWH) = Total air compressor requirements (KWH/YR)

KW = Total rated power requirements in kilowatts (.746KW = 1HP)

D - Diversity Factor - Estimated percentage of ON/OFF cycle time

HOURS - Average hours per week buses operate

Therefore:

AC(KWH) = 3.73 x .5 x 40 x 52
= 3,879 KWH/YR

4. LIGHTS

L(KWH) = KW x D x HOURS x 52 WEEKS/YR

Where:

L(KWH) = Total lighting requirements (KWH/YR)

KW = Total rated power requirements in kilowatts (1,000 Watts = 1KW)

D - Diversity Factor - Estimated percentage of total light KW on at a given time

Average hours per week lights are utilized

Therefore:

L(KWH) = 1.36 x .27 x 20 x 52
= 382 KWH/YR

APPENDIX B:

"Roll-Down" Test Methodology

This paper describes a method for determining aerodynamic drag and rolling resistance for a GMC RTS II transit bus. Rolling resistance (Kr) and aerodynamic drag (CdA) are computed for use as inputs to a simulation of a fuel cell powered transit vehicle.

Aerodynamic drag and rolling resistance are the principal forces which retard a rolling vehicle. The vehicle encounters aerodynamic drag increases with the square of the velocity. Rolling resistance results from road-tire resistance and drag in the drive train and transmission.

By coasting a vehicle from a maximum speed down to a stop, and measuring its velocity and distance at measured time intervals, the coefficient of drag and rolling resistance may be computed by the following method. This procedure is refered to in this text as "roll-down" or "coast-down" testing.

Lynn (1979) described straight line vehicle motion in a set of equations as follows:

1) $$F = \frac{w}{a}\,\frac{dv}{dt} + W(Kr + \sin) + \frac{pCdA}{29.94}\,(v+w)^2$$

Where: F = road force, lbs.

W = vehicle weight, lbs.

v = vehicle velocity, MPH

a = acceleration of gravity, 21.95 MPH/sec

w = velocity of wind component parallel to vehicle and in opposite direction, MPH = slope, degrees

t = times seconds

Kr = rolling resistance

p = air density, lb/ft3 (p = 0.0766 at 15 C, latm)

Cd = drag coefficient

A = frontal area, ft2

When the vehicle is coasting, F=0 and vehicle acceleration = (v), then:

2) $$v = - 21.95\ (Kr + \sin) - \frac{p\ CdA}{1.364W}\ (v + w)^2$$

Assuming a constant grade with a wind velocity at zero, v can be plotted as a linear (first degree polynomial) function of v2. The linear regression line can then be used to calculate Kr and CdA.

In practice the effects of wind cannot be eliminated from coast down testing. Therefore it is necessary to coast down the vehicle, with half of the runs in one direction and an equal number of runs in the other. For convenience, runs are labeled west or east.

As the vehicle coasts to a stop, the aerodynamic drag approaches zero. At w = o only the Y intercept portion of the acceleration equation containing Kr remains. Averaging the west and east intercepts:

3) $$Kr = \frac{(Yw + Ye)/2}{21.95} - \sin$$

The effect of wind results in slope differences in the regression lines. Figure 4 and 5 illustrates the linear regression plots for each direction and shows a west to east wind of approximately 5 mph.

The slope of the linear is given as:

4) $M = \frac{p \quad CdA}{1.364W}$

averaging the slopes to eliminate the wind we obtain;

5) $\frac{Mw + Me}{2} = \frac{p \quad CdA}{1.364W}$

rearranging;

6) $CdA = \frac{1.364W}{2p} (Mw + Me)$

METHODS

A GMC RTS II Transit bus provided by the City of Albuquerque, Sun-Tran bus system served as the test vehicle throughout the study. To collect acceleration and velocity data, we used a Nu-Metrics K5000 Mobile Distance Processor (MDP) and P-5000 printer. The instrument measures revolutions of a tire by means of a proximity switch. This switch senses 8 metal targets placed around the wheel rim and sends a pulse to the MDP microprocessor each time it passes a target. By means of a previously entered calibration number, the microprocessor converts the pulse to total feet traveled.

In the instrument's "TSD MODE", the maximum sampling rate for velocity, time, and distance is 5 seconds when interfaced with the printer. Velocity is differentiated by difference during the last second of each counting cycle. It was found that the sampling rate could be increased to 3 seconds by disconnecting the printer and reading the digital display only.

The coast down tests were conducted on the taxiway of the Double Eagle II Airport. At the time of the test the asphalt surface was new, with a constant slope of .5714% for 2800 feet. For the bus to coast down from 55 mph to 0 mph, a longer track would have been necessary to observe all the velocity changes with time. Since the track permitted runs over a much smaller range of velocities, it was necessary to mathematically connect these runs to give a smooth velocity curve from maximum speed to zero.

"Roll-down" tests were conducted shortly after sunrise to minimize wind and gust conditions. During testing, air temperature and pressure were checked and the wind velocity and direction was measured. Calibration of the MDP on the test track showed it to be accurate to 0.1% over the 2800 foot course. To minimize the effects of wind, an equal number of runs were made in each direction at initial speeds ranging from 10-45 mph.

By plotting the measured acceleration against the velocity squared, the values of Kr and CdA can be determined. Acceleration must be determined from the collected velocity data by differentiation. Differentiating velocity at five second intervals by difference would have introduced considerable error into the calculation. Also, it would have been extremely difficult to piece together the run segments to obtain a smooth velocity curve with respect to time since no exact starting time existed at the beginning of each run.

To overcome these problems, each run segment was subjected to a least squares curve-fitting routine yielding a best fit polynomial for each segment. The first derivative of each segment polynomial was taken, allowing a predicted acceleration to be calculated from each observed velocity.

The test track slopes downward -.5714% from west to east. Therefore, predicted acceleration values from west to east runs had to be adjusted by subtracting the acceleration of gravity from each observation. Similarly, east to west runs had to have the acceleration of gravity added. For small slopes this can be calculated by:

$$7)\quad v\ \text{down} = v - \left(\frac{\text{slope\%} * 21.95}{100} \right)$$

Predicted accelerations corrected for acceleration due to gravity were plotted against the observed velocity squared. After calculating the Y intercepts by y = b + ax linear regression analysis for east and west runs, CdA and Kr was computed using equations 3 and 6.

Air density (p) affects the aerodynamic drag coefficient and must be determined to calculate CdA. The density of dry air was given as:

p = po(To/T) (P/Po),

Where: po = 0.0766 lb/ft3 at 15 degrees celsius,

To = 273 degree K + 15 degrees = 288

T = 273 degrees K + ambient temperature degrees C.

Po = 1 std. atm. (29.92 in. Hg.)

P = atmosheric pressure in. Hg.

RESULTS

Time/velocity run-segments were subjected to three polynomial, least-squares curve fitting routines. They are the quadratic, c + bx + ax2; the cubic d + cx + bx2 + ax3; and c + bx + ax3. By estimating the sum of squares error for each fit, it was found that the quadratic gave the best fit consistently. Its derivative predicts a linear acceleration which agrees with the physics of the experiment. Figure shows a run with the best fit curve, spline-interpolated over the data. West and east predicted acceleration versus velocity squared plots are shown separately with 95% confidence boundaries attached in figures (to be included in final report). Using the test weight of the GMC RTS II of 26400 lbs, the aerodynamic drag and rolling friction are computed as follows:

$$Kr = \frac{(.2122 + .2128)/2}{21.95}$$

$$Kr = 0.0097$$

$$CdA = \frac{1.364 * 26400}{2 * 0.0631} (8.06*10-5 + 9.61*10-5)$$

$$CdA = 50.42$$

The degree of accuracy of the experiment is indicated by the close approximate values of the east and west Y intercepts and the low sum of square errors resulting from v versus v2 plots.

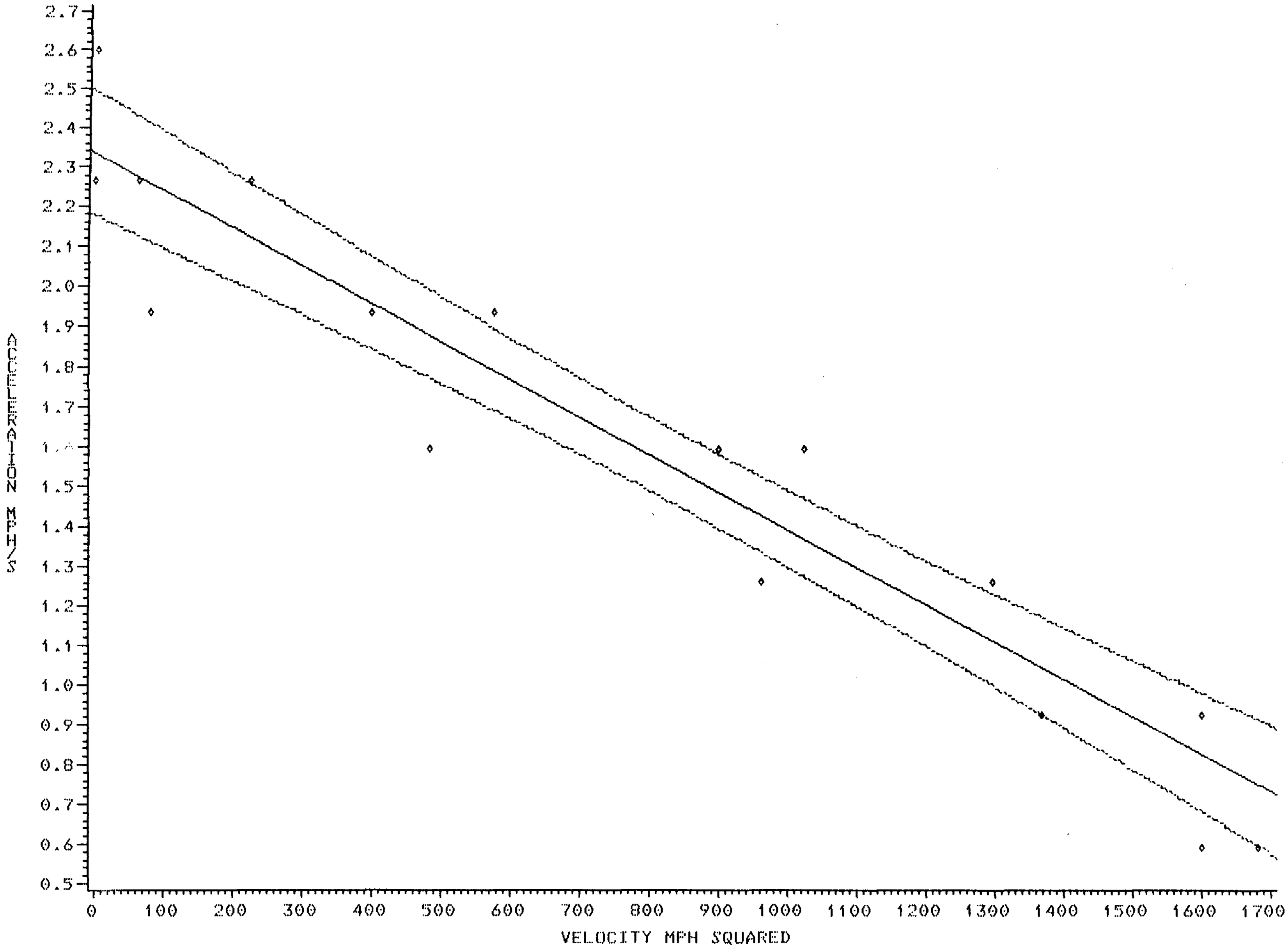
Problems were encountered during the "roll-down"experiments due to the fact that the bus under test had an automatic transmission. To provide lubricating oil to transmission, the bus had to be coasted in neutral while running the engine at high RPM. The bus had a tendency to try to go into gear at speed of less that 15 mph. These times were noted and corresponding data points were eliminated from the data set.

REFERENCES

D.K. Lynn et al., "Determination of Vehicle Rolling Resistance and Aerodynamic Drag." Proc. 29th Vehicular Technology Conf., Arlington Illinois, March 28-30, 1979.

ACCELERATION VS. VELOCITY FOR GMC RTSII

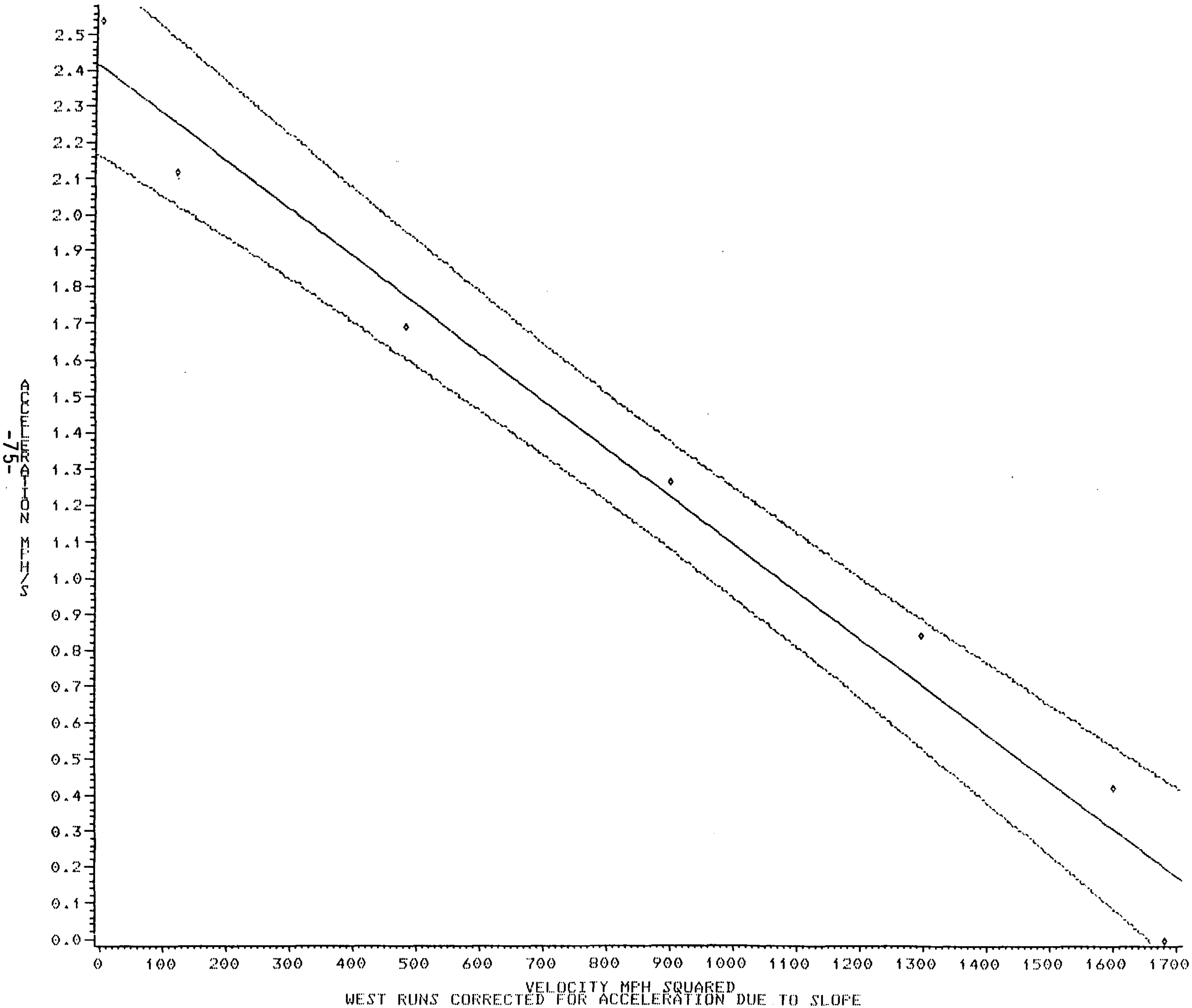
WITH 95 PERCENT CONFIDENCE LIMITS, MAX. ACCELERETION



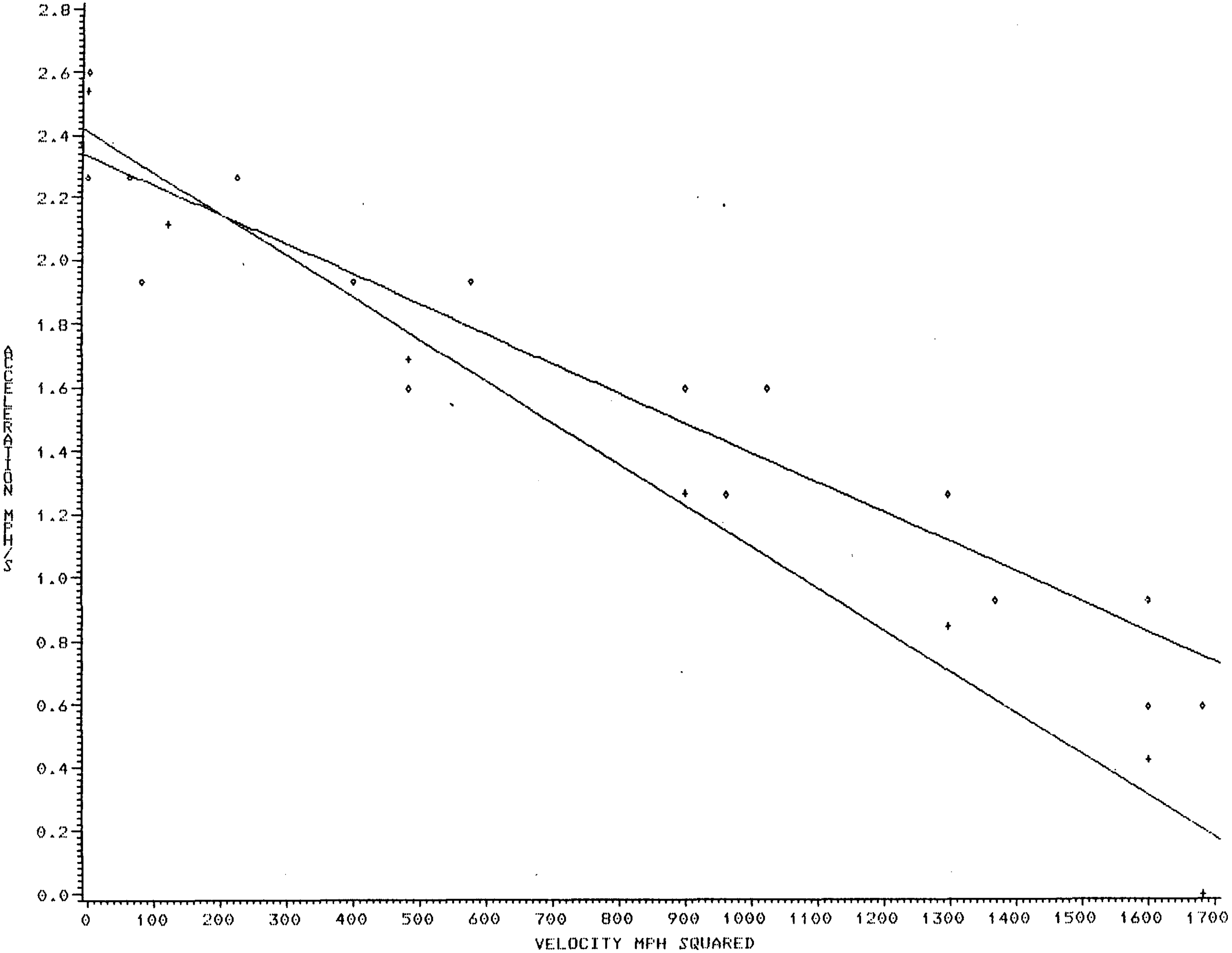
EAST RUNS CORRECTED FOR ACCELERATION DUE TO SLOPE

ACCELERATION VS. VELOCITY FOR GMC RTSII

WITH 95 PERCENT CONFIDENCE LIMITS, MAXIMUM ACCELERATION



WEST RUNS CORRECTED FOR ACCELERATION DUE TO SLOPE

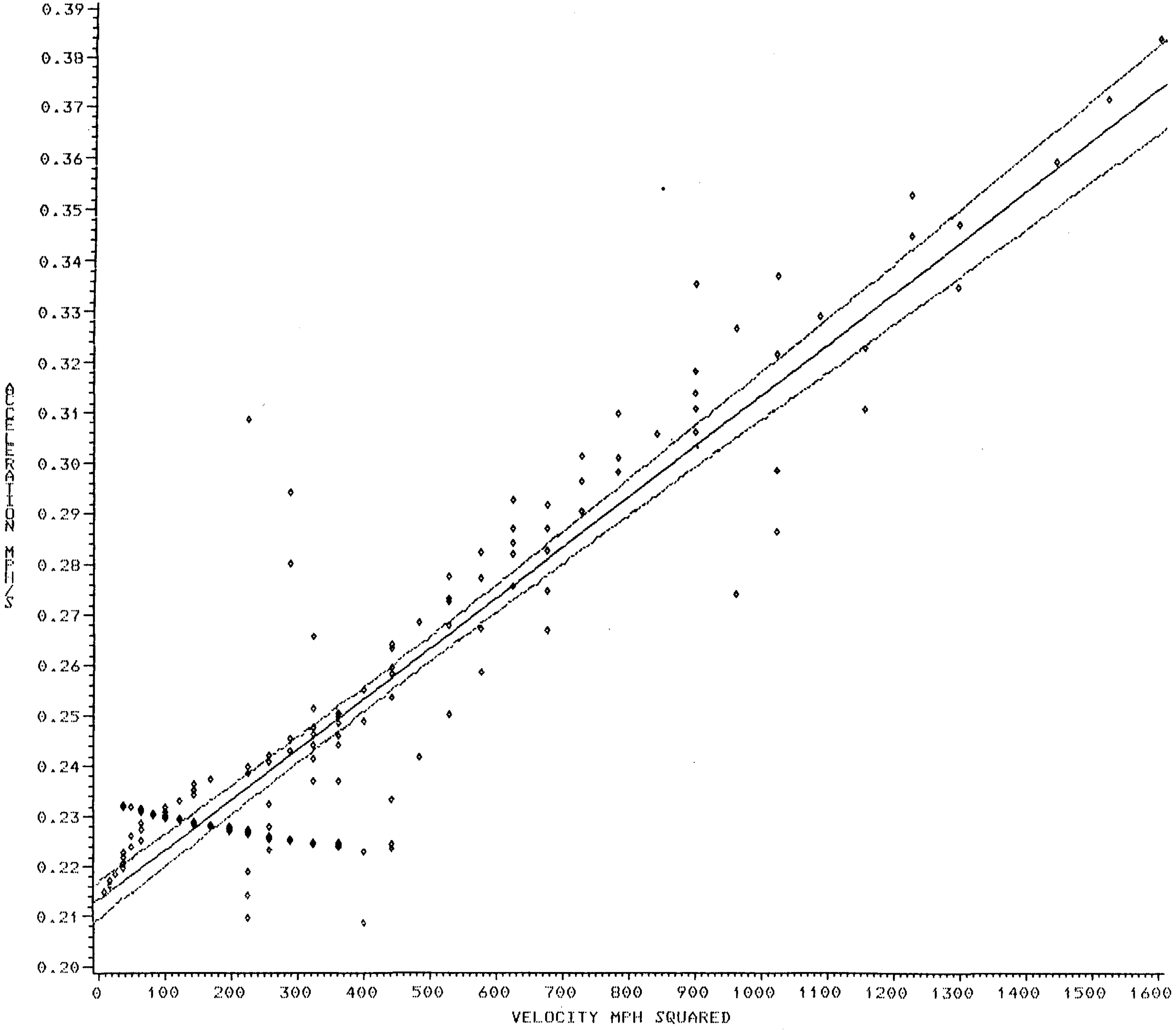


ACCELERATION VS. VELOCITY FOR GMC RTSII

MAXIMUM ACCELERATION

ACCELERATION VS. VELOCITY FOR GMC RTSII

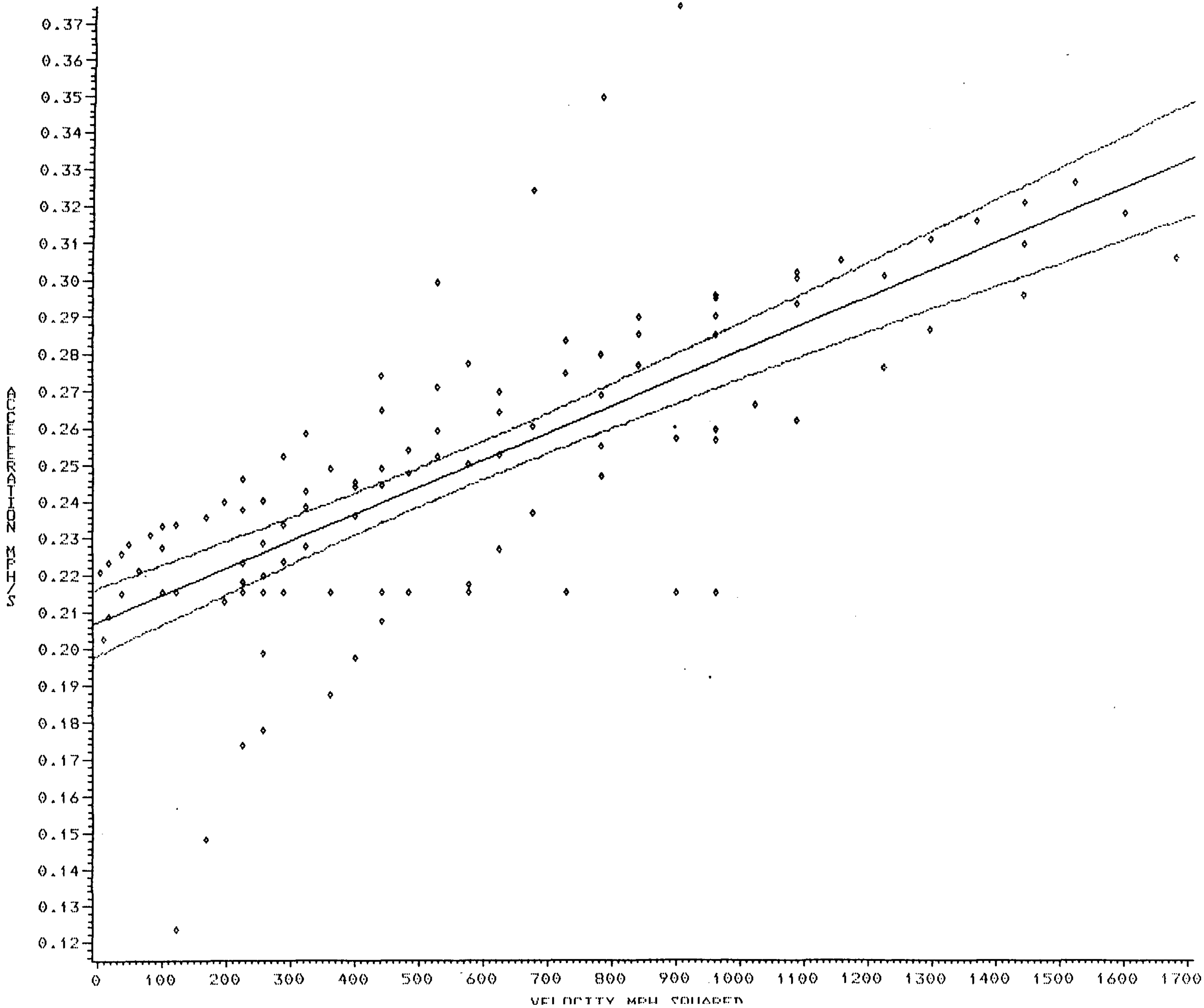
WITH 95 PERCENT CONFIDENCE LIMITS(BOTH DAYS)



EAST RUNS CORRECTED FOR ACCELERATION DUE TO SLOPE

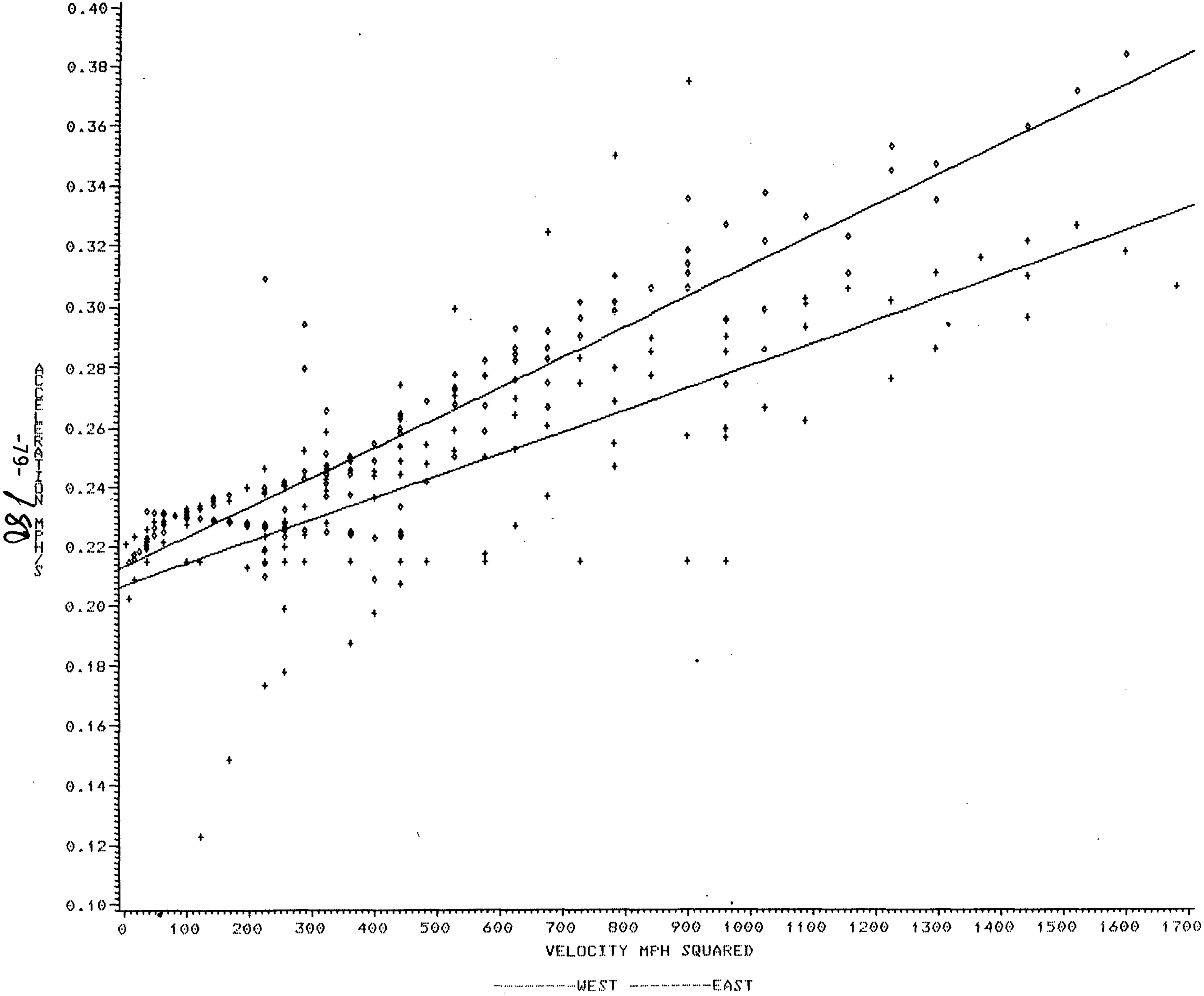
ACCELERATION VS. VELOCITY FOR GMC RTSII

WITH 95 PERCENT CONFIDENCE LIMITS(BOTH DAYS)



ACCELERATION VS. VELOCITY FOR GMC RTSII

BOTH DAYS



APPENDIX C:

"Duty Cycle" Data Collection Methodology

This paper describes a method of obtaining speed, time, and distance data from an intra-city transit bus under actual operating conditions. The data collected is used to determine road force requirements and "duty cycle" operating conditions for use in a simulation of a fuel-cell powered transit bus.

Fuel cells produce power at rates and for durations that are substantially different from their diesel engine counterparts. Road force, which is used to compute the number of pounds of thrust needed to run a vehicle varies as the vehicle moves from a stop to its maximum speed. This road force varies as the vehicle negotiates grades and as the passenger load changes. The power plant is therefore required to produce a constantly changing amount of thrust over a varying range of loads, grades, accelerations, and durations. This continuously changing demand on the vehicle power plant is refered to as its "duty cycle." The fuel cell must be capable of producing enough thrust to allow it to perform in a manner similar to that of a diesel powered bus. In order to size a fuel cell to power a transit bus, it is necessary to compute the road force and power requirements of a conventional diesel bus throughout its "duty cycle."

Time, speed, distance, grade, and load information was collected on three actual City of Albuquerque Sun-Tran bus routes using the GMC RTS II transit bus as a test vehicle. This real time "duty cycle" data will be used as part of a fuel-cell powered transit vehicle feasibility study.

METHODS

A GMC RTS II transit bus provided by the City of Albuquerque, Sun-Tran bus system served as the test vehicle throughout the study. To collect velocity, time, and distance data, we used a Nu-Metrics K5000 Mobile Distance Processor (MDP) and P-5000 printer. The instrument measures revolutions of a tire by means of a proximity switch. This switch senses 8 metal targets placed around the wheel rim and sends a pulse to the MDP microprocessor each time it passes a target. By means of a previously entered calibration number, the microprocessor converts the pulse to total feet traveled.

In the instrument's "TSD MODE", the maximum sampling rate for velocity, time, and distance is 5 seconds when interfaced with the printer. Velocity is differentiated by the difference during the last second of each counting cycle.

Three bus routes were selected for this study. These routes: the 90 N. Coors express, the 3 Louisiana-Central, and 13 University-Comanche, represent the widest range of operating conditions that are encountered by the Sun-Tran system. The 90 is a high speed commuter freeway to downtown run of about 15 miles. The 3 runs through some of the highest traffic density shopping center areas in Albuquerque with many stops and starts and high boarding and alighting volumes. The 13 route encounters altitude changes from 5000 feet to over 6500 feet in an eight mile grade.

Collected data was computer encoded into two data sets for processing under SAS.

The first data set was created using map distances and altitudes taken from 1:250 aerial topographic maps supplied by the City of Albuquerque Traffic Engineering Department. This data showed map distances along the bus routes at intervals of 250 feet with altitudes plus or minus one feet. The map data set was encoded with a number called a "stop number" assigned at each of the intervals of 250 feet. Slopes at 250 intervals were generated by dividing the difference in consecutive altitude observations by 250 feet. Multiplication by 100 gave grades in per cent at intervals of 250 feet.

The second data set was composed of time, distance, and velocity as measured on-board the bus on the selected routes. These "real time" measurements were made by the MDP in its TSD mode at 5 second intervals. The data collector manually noted each street intersection stop on the printer tape as they were encountered during data collection. Each set of observations therefore had distance, velocity, and time at five second intervals as well as the total passenger load at each stop for the duration of each route. The real time data was then encoded with the appropriate street intersection stop number from the map data set. The real time data set and the map data set were then merged by stop numbers so as to include grade information with the time, distance, and velocity observations occuring at each intersection.

In order to provide the merged data set with a more complete compliment of grades, the computer was asked to determine the number of intervals at 250 feet (n)[1] between each stop. It then incremented the real time distance occuring at the stop by the real time distance difference between stops divided by n an n number of times. The computer was then asked to match these n numbers of 250 foot map data points with the real time data points of corresponding distance. This gave grade information to each real time data point which occurred at intervals of 250 feet throughout the data set.

RESULTS

A sample of the "duty cycle" data is shown on Page 26. For more information or copies of the completed cycle print-out, see the "Report Information Sources" on Page 90.

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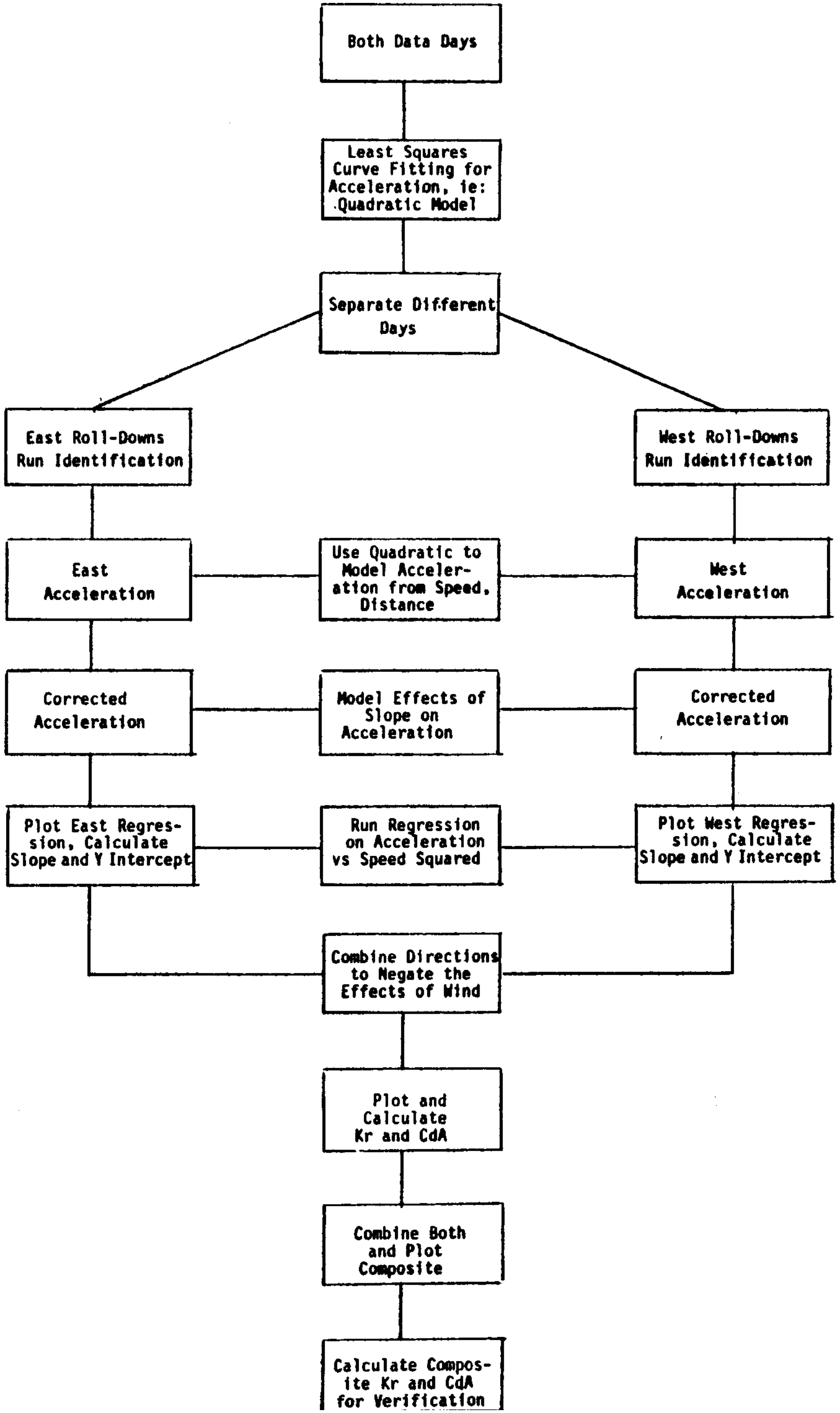
[1] n= stop number at stop A - stop number at stop B
d= real time distance at stop A - real time distance at stop B
dn= stop data point at 250 feet interval
d1= real time distance at stop A + d/n
d2= d1 = d/n
dn= dn - 1 + d/n

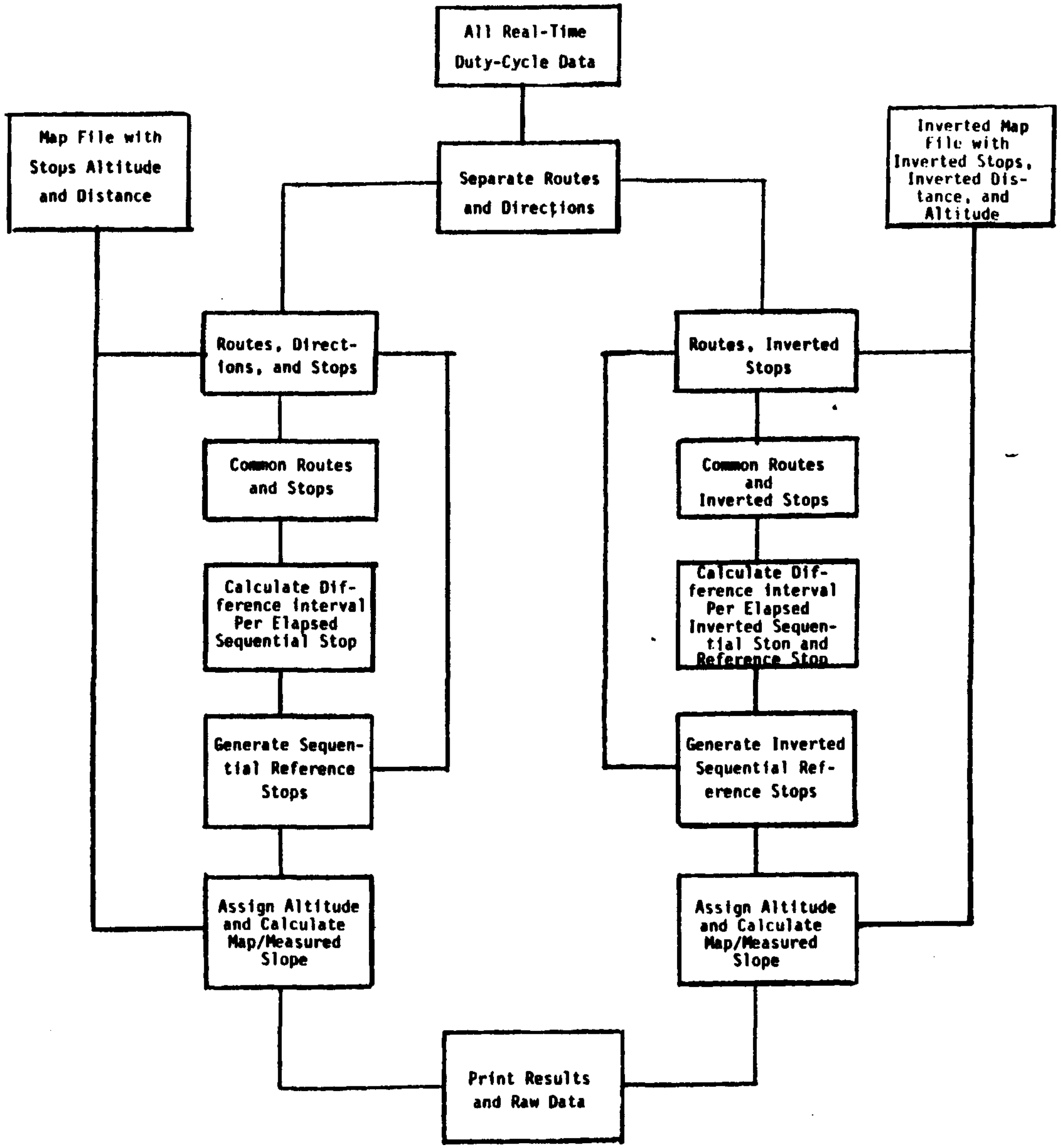
APPENDIX D:

Computer Program Logic Flowcharts For “Roll-Down” And “Duty Cycle” Manipulation

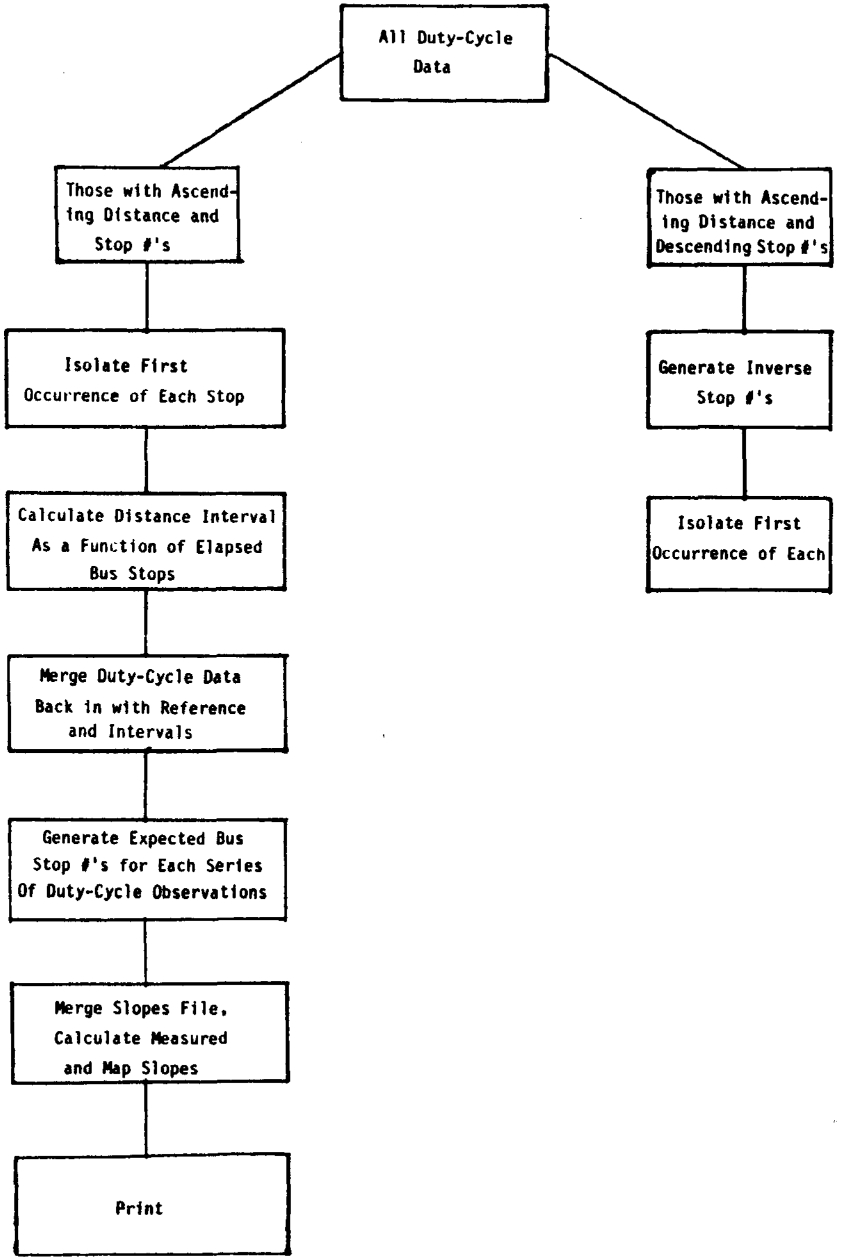
ROLL-DOWN PROGRAM LOGIC FLOWCHART



DUTY-CYCLE PROGRAM LOGIC FLOWCHART



DUTY-CYCLE PROGRAM LOGIC FLOWCHART



REPORT AND INFORMATION SOURCES

Additional copies of this report "Analysis of Municipal Bus Operations for the Advancement of Fuel Cell Technology", are available from:

Publications and Distribution
Public Technology, Inc.
1301 Pennsylvania Avenue, NW
Washington, D.C. 20004

For additional information on the tests and information presented in this report or for further information on the energy management programs in the city of Albuquerque, please contact:

Glenn Coontz or Mike Minturn
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Environmental Health and Energy Department
P.O. Box 1293
Albuquerque, New Mexico 87103

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