U.S. Department
of Transportation

**Federal Transit
Administration**

East Tennessee Hydrogen Initiative
Task 2:

Transition of Bus Transit to Hydrogen - A Case Study of a Medium Sized Transit Agency

December 21, 2010

http://www.fta.dot.gov/research

Report Documentation Page

1. Report No. FTA-TN-26-7033-2011.2	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
East Tennessee Hydrogen Initiative: Task II - Transition of Bus Transit to Hydrogen - A Case Study of a Medium Sized Transit Agency

5. Report Date
December 2010

6. Performing Organization Code

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8. Performing Organization Report No.

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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Federal Transit Administration
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590
http://www.fta.dot.gov/research

13. Type of Report and Period Covered
Final Report,
September 2008 – December 2010

14. Sponsoring Agency Code
Federal Transit Administration

15. Supplementary Notes

16. Abstract
The current climate crisis and recent world events, including a global economic crisis and growing concerns over the availability and cost of petroleum fuels, has sparked a global interest in developing alternative, sustainable, clean fuel technologies for the transportation sector. While a multitude of alternative fuel and vehicle technologies have been presented, hydrogen is considered by many as the option of choice. However, the introduction of hydrogen as a new fuel option presents many challenges, including the issue of how to supply an appropriate refueling infrastructure to support the new fuel. This report addresses infrastructure needs to support the transition of a medium sized transit agency to operation using hydrogen fuel, using the Knoxville Area Transit (KAT) as a case study. Specifically, requirements for hydrogen bus fleets, production, storage, refueling and maintenance facilities, and facility personnel are addressed as well as the transition strategy for implementing the technology and associated costs are addressed.

17. Key Words **Hydrogen Bus; Hydrogen Infrastructure; Fuel Cell, East Tennessee Hydrogen initiative (ETHI)**	18. Distribution Statement **No restrictions**

19. Security Classif. (of this report) **Unclassified**	20. Security Classif. (of this page) **Unclassified**	21. No. of Pages **51**	22. Price

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Report No. **FTA-TN-26-7033-2011.2**

Federal Transit Administration

Sponsored by
Federal Transit Administration
Office of Research, Demonstration and Innovation
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, D.C. 20590
Available Online
[http://www.fta.dot.gov/research]

FOREWORD

This work was completed as part of the East Tennessee Hydrogen Initiative, the objective of which is to plan and initiate a hydrogen support structure in East Tennessee and involves both the University of Tennessee's Knoxville and Chattanooga campuses. This report focuses on identifying infrastructure needs to support the transition of a medium sized transit agency to hydrogen fuel. The analysis includes an examination of hydrogen-fueled bus technologies and the various facility changes that would be necessary to safely and efficiently accommodate the new technology. It also investigates the costs associated with the changes and introduces a transition strategy for completing these changes. The findings and recommendations identified in these areas are applied to the Knoxville Area Transit.

DISCLAIMER

ACKNOWLEDGEMENTS

This project was completed under Federal Transit Administration (FTA) contract FTA-TN-26-7033-2011.2. The authors wish to thank Patrick Centolanzi, FTA Transportation Program Engineer, and Henry Nejako, FTA Program Management Officer, for support and suggestions. Special thanks is also extended to Dr. Wayne Davis, Dean of the College of Engineering at the University of Tennessee, for support of this project.

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EXECUTIVE SUMMARY

The work presented in this report is part of the East Tennessee Hydrogen Initiative (ETHI), the objective of which is to plan and initiate creation of a hydrogen-based support structure in East Tennessee. This report focuses on the initiation of that support structure through the early adoption of hydrogen technology by transit agencies and focuses on the hydrogen support infrastructure requirements that are necessary to complete the transition to hydrogen fuels. The work presented here was conducted at the University of Tennessee, Knoxville, as Task 2 of Federal Transit Administration (FTA) contract FTA-TN-26-7033-2011.2.

Widespread public adoption of hydrogen technology fuels is a large undertaking and faces many obstacles. The transition of transit agencies such as KAT as initial adopters can serve as an intermediate step. This project provides an example from which medium sized transit agencies, which are considering a transition to hydrogen fuels, can utilize in the planning and design of hydrogen-fueled transit systems. While this work focuses on the transition of KAT to hydrogen fuel, the findings are applicable to other transit agencies of similar characteristics. Furthermore, a number of benefits from the transition are identified; however, these benefits are based on assumptions made the maturation of hydrogen technology. Continued review of hydrogen technology is necessary to establish current performance levels for the various systems discussed here.

Data from demonstration projects around the country is used to analyze the current state of hydrogen bus technology, and future year projections are made based on data from other sources. The current and future year analysis is used to identify a number of requirements for medium sized transit agencies making the transition to hydrogen fuel. The Knoxville Area Transit (KAT) is used as a case study, and support infrastructure requirements are applied to the KAT existing transit system. The major findings of this work have implications for the transition of medium sized transit agencies to hydrogen fuel:

- Current performance and reliability limitations for hydrogen-fueled buses indicate a need to increase transit fleet sizes to maintain current service demands and availability standards. For KAT, a fleet size increase from 93 buses to 132 buses will be required, although improvements in hydrogen bus technology may reduce that requirement. Some sources indicate that as the technology matures there will be no requirement to increase fleet sizes to complete the transition to hydrogen fuel.

- Supporting a transit fleet of hydrogen-fueled buses will require hydrogen production, storage, and dispensing infrastructure. A comparison of hydrogen production technologies reveals that production via steam methane reformer has benefits over electrolysis. Notably, hydrogen production costs for Knoxville range from $4.18 to 4.82/kg for natural gas reformation and from $6.64 to 6.66/kg for electrolysis.
- It is estimated that between 835kg and 1200kg of hydrogen storage will be required to support the demand from hydrogen-fueled buses at KAT depending on the maturity of the bus technology. It is also estimated that a minimum of three hydrogen dispensers is necessary to reduce refueling time per day to a manageable level, which can be completed in off-peak hours.

- To adequately service the hydrogen-fueled bus fleet, new or modified maintenance and refueling facilities are required. Based the extent of upgrades required, the construction of new, separate facilities for maintenance, refueling, and washing operations for hydrogen-fueled buses is recommended. To support an increase in fleet size to 132 buses, an increase in maintenance bays from 12 to 17 is required, or one additional service bay per 8 new hydrogen-fueled buses. This requirement may be reduced as hydrogen technology matures. A phased construction and conversion of maintenance facilities would be recommended to compliment the phased transition.
- With the addition or modification of new facilities, a number of safety measures must be incorporated to safely incorporate the change to hydrogen fuel. This work identifies best practices to be incorporated in new facilities for maintenance, refueling, and washing procedures for hydrogen-fueled buses.
- In addition to facility upgrades, personnel changes are likely to be required, and additional training for all personnel will be necessary due to changes in technology and fuel.
- Best practices for hydrogen refueling station location are identified to provide adequate service to the transit fleet as well as to promote hydrogen technology to the public. This work utilizes a GIS model to apply these practices to the KAT, and a set of optimum locations for a hydrogen refueling station are identified, which would provide access to approximately 49% of the Knox County within a five mile radius and approximately 86% of the Knox County within a ten mile radius.
- A phased transition to hydrogen fuel is recommended, and transition strategies for completing the transition are discussed. Approximate bus replacement strategies are introduced for KAT, and estimated costs associated with these strategies are given based on varying fleet requirements due to maturity levels of hydrogen technology. These estimates are compared to KAT's current operating expenses, and a reduction in operating expenses of approximately $2.7 million is identified if these scenarios become reality.

In addition to identifying key infrastructure requirements for the transition to hydrogen fuel, this work relates directly to the FTA's strategic plan, particularly Goal 1, to provide national transit research leadership, and Goal 3, to support improving the performance of transit operations and systems. This work provides a framework for which transit agencies can base their transition to a hydrogen-fueled bus fleet by identifying the necessary requirements that such an agency must address. This framework corresponds to FTA Strategic Research Goal 1, Objective 1.1, to provide vision and prepare the nation for transit advancements, and to FTA Strategic Research Goal 1, Objective 1.3, which is synthesize research results to provide useful bodies of knowledge for transit industry decision makers and to shape the national transit research agenda. As the transition discussed by this report is to hydrogen-fueled buses, a number of benefits may result from the transition, placing this work in line with FTA Strategic Research Goal 3, Objective 3.4, to investigate the use of high-efficiency technologies and alternative energy sources, and FTA Strategic Research Goal 3, Objective 3.5, to perform research to reduce transit environmental impacts.

1. INTRODUCTION

1.1 PROJECT BACKGROUND

The current climate crisis along with recent world events, including a global economic crisis and growing concerns over the availability and cost of petroleum fuels, has sparked a global interest in developing alternative, sustainable, clean-fuel technologies for the transportation sector. While a multitude of alternative fuel and vehicle technologies have been presented, hydrogen is widely considered to be the option of choice. In 2002, President George W. Bush introduced the Hydrogen Fuel Initiative, a vision of a future hydrogen economy in the United States. A hydrogen economy would effectively increase energy security, environmental quality, energy efficiency, and economic competitiveness for this country [1]. This has been echoed more recently in the 2008 Presidential Election as both Presidential Candidates emphasized the importance of developing a "green economy" in the United States.

Hydrogen has long been considered an option by many as a possible transportation fuel for the reasons listed above. However, the transition to introducing a new fuel source such as hydrogen has many obstacles including the issue of building an appropriate fueling infrastructure. Without an adequate fueling infrastructure, consumers will likely be reluctant to purchase hydrogen-powered vehicles. Conversely, the lack of a sufficient number of hydrogen vehicles makes it difficult to build and support a fueling network. One approach is to initially develop infrastructure for the use of public agencies or other agencies that operate fleets, which could also be utilized by the public. Analysis suggests that the cost of introducing hydrogen can be reduced by selecting a mode that uses a small number of relatively large vehicles, which are operated by professional crews along a limited number of routes or within a small geographic area [2]. A report done by the Government of Canada through the Canadian Transportation Fuel Cell Alliance identifies urban transit systems, currently operating bus fleets fueled almost exclusively by diesel, as natural early adopters of hydrogen technology [3].

The work presented here is a part of the East Tennessee Hydrogen Initiative (ETHI) and focuses on analyzing the full transition to a hydrogen fuel infrastructure to support hydrogen-powered buses. While demonstration projects have focused primarily on supporting and operating hydrogen-powered buses on a limited number of lines, this report considers the transition of a full transit system to hydrogen fuel. Other work centered on adoption of hydrogen technology has included a larger scale, often nationwide, analysis, where this work focuses on the implications to an individual transit agency. Specifically, this report will identify a number of requirements that would be necessary in the transition of a medium sized transit agency to a hydrogen-fueled bus fleet. Identified here are bus fleet requirements including power train technology, maintenance and reliability measures, and fleets size requirements; refueling infrastructure requirements, which includes an analysis of station capacity requirements as well as a comparison of various methods for producing hydrogen fuel; facilities and personnel needs that hydrogen powered bus fleets will require; and, lastly, an investigation into hydrogen refueling station siting.

1.2 ETHI PROJECT OVERVIEW

This work is part of the East Tennessee Hydrogen Initiative, the objective of which is to plan and initiate creation of hydrogen-based infrastructure in East Tennessee. The effect of creating such a support structure will lead to the development of technologies that will reduce emissions of air pollution through the utilization of hydrogen-based energy systems and reduce the transportation industry's dependence on the use of foreign oil. Furthermore, this project will better position the East Tennessee area and the Federal Transit Administration to participate in the technological and economic benefits of a hydrogen economy. Both the University of Tennessee's Knoxville and Chattanooga campuses are working in collaborative efforts with commercial, industrial, university, federal, state, and local agency partners on the development of a hydrogen industry for the East Tennessee area.

The research conducted for this project relates to the development of technologies that will allow for and enhance the ability to utilize hydrogen-based technologies for the fueling of both light duty and heavy duty vehicles, including vehicles utilized in transit operations. It also addresses issues such as the storage of hydrogen to be used as fuel, safety issues that exist with the new technology, on-board fuel cell and internal combustion technologies, and the hydrogen infrastructure itself as it relates to hydrogen production and hydrogen delivery. This research has been divided into three separate tasks to address the issues above.

Task I addresses new and improved ways of on-board storage of hydrogen, with the focus being the development and evaluation of Metal Porhyrin Frameworks (MPFs) and Decorated Carbon Fullerenes (DCFs) that have the potential to store hydrogen at reduced pressures and allow for higher densities. Task II is to investigate the resource requirements necessary to transition an entire transit fleet from diesel, bio-diesel, or compressed natural gas (CNG) fuel sources to hydrogen. Task II will use the Knoxville Area Transit (KAT) as a case study and is the subject of this report. Task III involves locating a 1-2 kg/day hydrogen fueling station on the University of Tennessee campus, which will be used in support of Task I and Task II. Task III will also provide the University with hands-on experience on the operation of a fueling station, the fueling of a hydrogen internal combustion engine (HICE) vehicle, and the opportunity to conduct research on the alternative storage of hydrogen using technologies developed in Task I.

1.3 SCOPE OF ETHI TASK II

Task II investigates the resource requirements necessary to transition an entire fleet of transit vehicles from diesel, bio-diesel, or CNG fuel sources to hydrogen. The KAT agency will be used as a case study for this analysis; however, the findings from this research can be generalized and applied to other transit fleet operations. Data and analysis compiled for Task II will be drawn from a combination of local operating conditions, existing published documents on hydrogen demonstration projects, interviews with transit managers who have experience with hydrogen vehicles, as well as other sources in order to compile experiences and potential challenges.

This research will consist of five key components: 1) fleet requirements and composition, 2) refueling infrastructure, 3) facilities and service requirements, 4) fuel transition requirements, and 5) the timeline, projected costs, and uncertainty. The fleet requirements analysis component of Task II will review vehicle power-train technology, maintenance and reliability, and fleet size requirements and will also investigate and compare the use of hydrogen fuel in internal combustion engines (ICE) and fuel cells. Furthermore, it will review the results of hydrogen bus demonstration projects to determine fleet size requirements. The refueling infrastructure component will investigate strategic and visible site locations for the refueling station. It will also examine station capacity and hydrogen storage and generation as well as the environmental, distributional, and economic impacts relating to hydrogen production and storage. Facilities and maintenance personnel requirements will be investigated in the facilities and service requirements component. The fuel transition component will investigate a number of strategies for phasing in the hydrogen fuel infrastructure. Lastly, the costs and timeline component of the research will identify costs over time of the various technologies and infrastructure requirements transition to fully adopting hydrogen as fuel for its entire transit fleet.

2. A REVIEW OF HYDROGEN TECHNOLOGY

2.1 CURRENT ENGINE TECHNOLOGY

Several of hydrogen's properties, including a wide flammability range, low ignition energy, low buoyancy, high diffusivity, and other properties, give hydrogen fuel characteristics that have significant impact to the hydrogen bus fleets and supporting infrastructure [4-7]. These properties are also important to propulsion system technologies. There are currently two types of technology available to propel a vehicle using hydrogen as fuel, the internal combustion engine (ICE) and fuel cells. Recently, there have been several documented attempts to develop and refine both the hydrogen ICE [4, 6, 8] and the hydrogen fuel cell vehicle [9]. The Hydrogen Road Tour, sponsored by the US Department of Transportation, featured many hydrogen-powered cars from a host of ICE and fuel cell vehicles traveling across the US. The tour allowed the public to view and test-drive the vehicles and emphasized the progress that has been made to date with hydrogen technology. Notably, hydrogen-filled trucks followed to road tour because of lack of refueling infrastructure.

While fuel cells are relatively new and expensive technology, ICE technology is more mature. Vehicles incorporating this technology, including hydrogen ICE buses, can cost considerably less than their fuel cell counterparts. However, the use of hydrogen in ICEs comes with its own challenges, including the emission of high amounts nitrogen oxides in exhaust, ignition and backfire problems, and relatively low power output as compared to other fuels [4, 6].

Hydrogen fuel cells support electric motors by harnessing energy stored in charged hydrogen. Hydrogen fuel cells emit no pollution at the tailpipe, and the only by-products are heat and water, produced from the chemical reaction of hydrogen with air. However, pollutants are likely emitted during the production of hydrogen depending on the production methods used. Still, these emissions can be reduced by approximately 60 percent in comparison to the emissions produced from operating a standard petroleum-based internal combustion engine [9]. Wang [10] provides a detailed comparison of various alternative fuels and vehicle technologies. Fuel cells operate using a simple reaction, which is highly efficient, and thus have been shown to have higher overall energy efficiency than ICEs [9]. Furthermore, because of the simple design of fuel cell systems, it is expected that fuel cell systems will have higher reliability, less running noise, and require less maintenance than ICEs [3].

Based on current technology, initially it may be more reasonable to choose hydrogen internal combustion technology for new hydrogen-fueled buses based solely on the maturity and cost of the technology. However, it is expected that the cost fuel cell technology will dramatically decrease over the next 5 to 10 years [3], making fuel cells a more competitive option financially. Cockroft [11] indicates that, in a long term scenario in which a hydrogen support infrastructure is developed, hydrogen fuel cell buses will have a better life-cycle cost than diesel and (CNG) buses. With decreasing cost of the technology and clear environmental benefits, the fuel cell stands out as a potentially superior technology for future hydrogen-fueled bus fleets.

2.2 HYDROGEN PRODUCTION METHODS

Diverse methods for hydrogen production provide different economic and environmental advantages that can vary depending on geographic location and the relative size of the refueling station or network of stations. There are two main options in particular, forecourt electrolysis, which can produce hydrogen through electrolysis of water via electricity provided by any source, and forecourt steam methane reformer (SMR). Another option is third party delivery of hydrogen fuel, and the use of alternative energy sources to power hydrogen generation is also a consideration. Hydrogen fuel can be stored as either low-pressure liquid hydrogen or as a high-pressure compressed gas; however, extremely low temperatures are required to liquefy hydrogen, requiring additional energy costs.

SMR production of hydrogen accounts for approximately 95 percent of the hydrogen currently produced in the United States [12]. This process utilizes natural gas to produce hydrogen fuel. The natural gas is reformed and then purified to produce a hydrogen-rich gas suitable for use as fuel. In electrolysis electricity is used to extract hydrogen from water. In general, this process is not as energy efficient and is generally more expensive than forecourt SMR; however, a number of potential new technologies for electrolysis may provide additional benefits, such as reducing the electricity requirement with natural gas assisted electrolysis and improving the efficiency considerably [13].

Each method has potential environmental impacts as well. For SMR production, the primary by-product is carbon dioxide [12]. For electrolysis, the source of the electricity used in the process could contribute additional pollutants. Lipman [13] provided a detailed review of the relative environmental benefits of various hydrogen production methods. For the KAT case, the electricity used may come primarily from coal burning plants, and while the electricity may be relatively cheap, the pollutants emitted during the generation of the electricity used would still be significant.

2.3 LESSONS LEARNED FROM DEMONSTRATION PROJECTS

Through review of current hydrogen bus demonstration projects and the incorporation of estimates and predictions from other published sources, estimates are made about the requirements that would be placed on a medium sized transit agency making the transition to hydrogen fuel. A number of hydrogen-fueled bus demonstration projects have been planned or are underway at various locations around the United States and in other countries. Through funding from both the Department of Energy and the Federal Transit Administration, the National Renewable Energies Laboratory is operating a number of demonstration projects currently or scheduled to begin within the next few years [14]. Table 1 summarizes current and past hydrogen bus demonstration projects in the U.S.

Table 1. Currently Active and Past U.S. Fuel Cell Bus Demonstration Projects [14]

Project	City	State	Status
AC Transit ZEBA Demo (in partnership with other Bay Area Transit Agencies), UTC Power, Van Hool	Oakland	CA	Active
City of Burbank FCB Demo (Proterra)	Burbank	CA	Active
CT Nutmeg FCB Demonstration - UTC Power, Van Hool (FTA-NAVC)	Hartford & other TBD	CT	Active
CTTRANSIT FCB Demo (ISE/ UTC Power/Van Hool)	Hartford	CT	Active
Dual Variable Output FCB - Proterra/Hydrogenics (FTA-CTE)	Columbia, Austin (1 year each)	SC, TX	Active
SunLine Advanced Technology FCB (New Flyer, Ballard, ISE)	Thousand Palms	CA	Active
SunLine FCB Demo (ISE/UTC Power/Van Hool)	Thousand Palms	CA	Active
University of Delaware - Phase 1 (Ebus, 22-foot)	Newark	DE	Active
University of Delaware - Phase 2 (Ebus, 22-foot)	Newark	DE	Active
University of Texas (Ebus)	Austin	TX	Active
US Air Force/Enova/Hydrogenics/HTDC	Honolulu	HI	Active
AC Transit HyRoad (ISE/UTC Power/Van Hool)	Oakland	CA	Active
Santa Clara VTA FCB Demo (Gillig/Ballard)	San Jose	CA	Complete

This paper reviews a selected group of these projects from which data have been collected and are currently available. Information on current reliability and performance levels as well as various safety specifications was obtained from progress reports for the demonstration projects [15-17]. These reports also provided great insight into specific problems encountered with the new technology that affect the reliability of the buses as well as modifications to facility designs. The Hydrogen Demand and Resource Analysis (HyDRA) Model [18] was used to estimate costs associated hydrogen production methods.

Based on findings from these sources, estimates about expected current and future performance levels and various facility needs were made. Information on KAT's current bus fleet, facilities, personnel, and other information was obtained through various meetings and interviews with KAT personnel. Projections about transition requirements were applied to KAT based on the information provided by the transit agency.

Performance and reliability data from Alameda-Contra Costa Transit (AC Transit), Santa Clara Valley Transportation Authority (VTA), and SunLine Transit Agency were reviewed. Average availability from the hydrogen-fueled buses at these sites ranged from 55 percent to 66 percent over the periods observed, which is significantly lower than the average availability for other bus types although this is partially due to learning and troubleshooting the new technology. Total mileage is lower for the hydrogen-fueled buses in each case because special routes or limited service hours were enacted for these buses. Performance and reliability data for hydrogen-fueled buses at the demonstration sites is shown in Table 2 along with corresponding data for other bus types operated during the same period for comparison.

Table 2. Hydrogen Bus Reliability Data [15-17]

Demonstration Site	AC Transit		SunLine Transit Agency			Santa Clara VTA	
City	Oakland		Thousand Palms			San Jose	
State	California		California			California	
Bus Type	Fuel Cell	Diesel	Fuel Cell	HICE	CNG	Fuel Cell	Diesel
Number of Buses	3	6	1	1	5	3	5
Average Monthly Mileage per Bus	987	3091	1886	1612	4359	809	4335
Availability (%)	55	N/A	66	59	83	58	85
Miles between Road Calls (MBRC All)	1,296	4,582	1,455	2,073	9,949	898	8,189
Propulsion Only MBRC	1,517	10,526	1,592	2,291	30,510	918	10,838
Total Maintenance ($ per mile)	0.57	0.44	0.44	0.59	0.3	3.55	0.54
Maintenance - Propulsion Only ($ per mile)	0.09	0.1	0.22	0.39	0.08	2.37	0.2

Another important metric derived from these data is that the total operating cost per mile for the hydrogen-fueled buses was typically higher than that of the other bus types. This relates to the relative maturity of diesel and compressed natural gas buses and the inexperience of the maintenance personnel with hydrogen technology. The road calls requirements compared to the other buses during these demonstrations indicate that there are some reliability issues with the hydrogen technology and further indicates why the average availability of these buses was lower.

On-site steam methane reformers were used to generate hydrogen fuel at both AC Transit and SunLine Transit Agency, while Santa Clara VTA used a third party to deliver liquid hydrogen to the site. The amount of hydrogen produced or delivered and on-site hydrogen storage volumes varied by site but other measures such as the average fill rate and the required time to refuel the hydrogen buses was consistent among the sites.

Given the characteristics of hydrogen fuel, facilities for maintenance, refueling, and bus washing had to be constructed or modified to safely and adequately service the buses at each site. Each facility required a number of safety measures be installed to ensure safety during maintenance procedures. Since a hydrogen leak resulting in fire risk is one of the most significant concerns, hydrogen detectors, fire detection systems, fire suppression systems, ventilation and other countermeasures were common among the safety measures installed.

2.4 CONSIDERATIONS FOR NEW REFUELING STATION LOCATIONS

The construction of new infrastructure and the renovation of existing infrastructure to support hydrogen-fueled vehicles has one key issue in addition to those previously discussed. As discussed previously, refueling stations must have adequate storage and dispensing capacity to support the new hydrogen-fueled vehicles. In this case, refueling requirements to support hydrogen-fueled buses were considered. This research, however, considers the adoption of hydrogen fuel by public agencies as a means toward introducing hydrogen fuel to the general public. Therefore, not only must these facilities serve the transit agencies, they must also serve as a means to expose the technology to the public for potential use, and this should be considered when selecting locations for the new hydrogen refueling stations.

Bouwkamp [19] stated that "Innovations will have a more rapid rate of adoption the higher the degree of relative advantage, compatibility, trialability, and observability and the lower the level of complexity." This means that for a new fuel such as hydrogen to be successful a number of things are necessary. First, hydrogen fuel must be perceived as a better alternative than traditional fuels, it must fit existing needs as a fuel source and be compatible to the existing infrastructure, and it must go through trials and demonstrations to prove it is a valid option. Hydrogen fuel technology must also be visible to the public so that they can judge its advantages, and it must not be perceived as being difficult to use. According to Bouwkamp [19], hydrogen fuel technology does not fare well when the aspects of compatibility, "trialability", and "observability" are considered. The "trialability" aspect is being addressed through the many hydrogen bus demonstration projects that are either currently ongoing or planned, and, with the introduction of hydrogen refueling stations through local transit agencies, the issues of compatibility and "observability" can begin to be addressed as well.

Many models have been created that investigate a network of hydrogen refueling stations. Melendez and Milbrandt [1] propose a network of hydrogen refueling stations located along major interstates throughout the United States. These stations are located within Metropolitan Statistical Areas (MSAs) and are optimized for passing interstate traffic, not necessarily local traffic. Furthermore, these proposed stations provide access to hydrogen fuel for a large population living near the station. According to Melendez and Milbrandt [1], 22.3 million people live within a five-mile radius of the proposed sites, and 58.2 million people live within a ten-mile radius of the sites. Locating these facilities where a large portion of the public has reasonable access to them and where they are highly visible to the general public is key to a successful transition.

Nicholas [20] employed a meso-level analysis to develop a macro-level estimation of station siting for the Sacramento, California, area. Nicholas developed a GIS model which minimized the region-wide average driving time to the nearest refueling station. The number of hydrogen fuel cell vehicles expected within the area was determined based on average household income. Areas with a higher average household income are expected to have a higher percentage of ownership of fuel cell vehicles. Nicholas' model used existing gasoline stations in the region as potential locations for the new hydrogen stations. Using a number of scenarios replacing between one station up to 319 stations, or all of the stations in the region, with hydrogen refueling stations, Nicholas found the average travel time to a hydrogen refueling station significantly decreased as the number of stations increased up to 96 stations; however, very little decrease in travel time was shown as the number of refueling stations increased from 96 to 319. Furthermore, for the Sacramento area a network of hydrogen stations of only 30% of the number of gasoline stations closely approximates the average travel times provided by the full network of 319 gasoline stations.

Swoon [21] also utilized a GIS to test initial distributions of hydrogen refueling stations located along German trunk roads for the potential to generate large-scale adoption of hydrogen fuel cell vehicles. Swoon suggests that travel time is not the only factor that should be considered in hydrogen station siting. Additional factors such as income, social status, public opinion, and individual driving patterns of individuals residing in the surrounding areas are also important considerations in refueling station siting. Swoon also identifies a "don't worry distance" factor, which relates to the distance between hydrogen refueling stations and the driver's worry over refueling. According to Swoon, the cumulative individual benefits, social benefits, and tax benefits of buying a fuel cell vehicle must outweigh the added costs of the fuel cell vehicle plus the amount of worry that an individual has over refueling in order for that individual to purchase a fuel cell vehicle.

Similar work was done by Stephan and Sullivan [22]. They present a utility function for drivers, which is the cumulative benefit of a number of factors minus a worry factor. Included in those factors are fixed benefits which represents non-mileage based benefits such as being environmentally friendly and high-tech, variable benefits which represent mileage based benefits, and a factor representing public opinion. The worry factor presented by Stephan and Sullivan [22] is similar to that presented by Swoon [21] by including refueling range anxiety.

While those authors focused on siting of hydrogen stations for a network of stations which would support hydrogen fuel cell vehicles owned by the public, this research is focused on the siting of hydrogen stations to support a fleet of hydrogen-fueled buses, which could ultimately be used to promote the widespread adoption of hydrogen technology and lead to ownership of hydrogen vehicles by the public. As with other aspects of the hydrogen support infrastructure, much can be learned about facility location from experiences at demonstration sites. At AC Transit, the Oakland Division was selected for demonstrating fuel cell buses, which is located in a light industrial area. The location was selected partly because of the available space for the refueling infrastructure needs [15]; however, locating refueling infrastructure in an area such as this significantly limits the visibility and access of the facility to the general public. Alternatively, Sunline Transit Agency's refueling stations are open to the public, and the agency benefits from the sale of fuel to the public [15]. This approach allows the public access to the alternative fuels provided at the stations including compressed natural gas and hydrogen. While most of the public may not own a hydrogen-fueled vehicle, having access to a source of hydrogen fuel promotes the technology as an alternative to gasoline or diesel.

It can be seen that access and visibility to hydrogen refueling stations are of great importance; however, when considering locations for the proposed refueling station, other issues must be considered. Concerns from area residents and businesses over the placement of a hydrogen station can cause significant delays in the construction and opening of a station [23]. Not-In-My-Back-Yard (NIMBY) issues are a serious concern when considering the placement of a hydrogen refueling station. Characteristics such as size, appearance, safety and overall public perception of the facility are important to whether the public will accept the chosen facility location. Hydrogen refueling stations constructed at demonstration projects have an industrial appearance that may not be welcomed in many residential areas. One concern that may cause objection is the appearance of above ground hydrogen storage tanks [20]. Also, the public in general is unfamiliar with the characteristics of hydrogen gas, and safety at such facilities may be a concern for many. Public awareness programs about the hydrogen facilities are recommended to build support and acceptance of new facilities.

2.5 APPLICABLE COSTS

A number of bus and system requirements necessary in making a successful transition to hydrogen technology have been specified. This section will identify some of the costs associated with those requirements. Cost estimates from a number of sources will be presented for the various technologies and infrastructure requirements, and those costs will be projected into the future as many of these costs are expected to decrease over time as the technologies mature.

The first of such costs that must be considered are those associated with the hydrogen bus fleet itself. Table 3 shows the purchase prices for hydrogen-fueled buses at demonstration sites. From this table, we can see that in 2004 and 2005 the average purchase price for a hydrogen fuel cell bus was approximately $3.27 million. This price in 2009 dollars would be approximately $3.56 million. The current purchase price is very high, but is expected to decrease at technology matures. The purchase price for a hydrogen ICE bus was between $1 million to $2 million in 2004 as reported by SunLine Transit. Low purchase prices for hydrogen ICE buses make them a strong candidate for initial hydrogen-fueled transit fleets.

Table 3. Costs of Hydrogen-Fueled Buses at Demonstration Sites

Demonstration Site	**AC Transit**	**SunLine Transit Agency**		**Santa Clara VTA**
No. Hydrogen Buses	3	1	1	3
Bus Type	Fuel Cell	Fuel Cell	HICE	Fuel Cell
Manufacturer	Van Hool	Van Hool	New Flyer	Gillig
Model	A330 Low Floor	A330 Low Floor	TB-40 Low floor	Low Floor
Model Year	2005	2005	2004	2004
Purchase Price	$3.2 million	$3.1 million	$1 million to $2 million	$3.5 million
Average Hydrogen Fuel Cell Bus Cost:			**$3.27 million**	

Current estimates place the purchase price for hydrogen fuel cell buses at approximately $2.5 million. This is a reduction of approximately $770,000 from the costs experienced by demonstration sites, and a reduction of approximately $1 million from the inflation adjusted purchase price. While a purchase price of $2.5 million per bus represents a significant investment, particularly for a small or medium sized transit agency, it does represent a significant improvement in the technology as well as increased commercial production of these vehicles. This would indicate that larger scale adoption of these technologies could reduce production costs even further, making the hydrogen fuel cell buses a more viable option. As mentioned by Homandinger [24], mass production techniques and economies of scale could lead to further reductions in bus price, which are likely attainable.

Table 4 shows one source's estimates for future purchase prices of hydrogen fuel cell buses. An average fuel cell bus price in 2015 of $952,256 would represent a significant reduction purchase price. The same source estimates the 2015 purchase price for a standard diesel bus to be approximately $570,000 [3]. From Table 5 we can see that this estimate is much higher than current capital costs for all common transit bus types, except for hybrid-diesel buses; but, as the capital costs for standard diesel transit buses increase and the costs of hydrogen buses reduce, hydrogen technology becomes a more attractive and economically feasible option. None-the-less, hydrogen buses need to make a business case that they are more attractive from an economic or environmental perspective than their counterparts.

Table 4. Future Year Hydrogen Bus Purchase Price Estimates [3]

Source	Fuel Cell Bus Cost		Fuel Cell Hybrid Bus Cost	
	2004	**2015**	**2004**	**2015**
1	1,903,365	971,434	1,420,224	967,960
2	2,499,677	1,034,604	1,778,011	1,005,862
3		843,107		890,964
4	1,745,673	954,727	1,325,608	1,024,514
5	1,770,972	957,408	1,340,788	959,545
Average:	**$1,979,922**	**$952,256**	**$1,466,158**	**$969,769**

Table 5. Transit Bus Lifecycle Costs [25]

	Bus Type			
	CNG	**ULSD**	**B20**	**Diesel Hybrid**
Capital Cost:	$371,116	$321,143	$321,143	$533,005
Fuel Costs:	$244,181	$268,830	$284,818	$226,629
Operation Costs:	$106,024	$87,117	$83,774	$148,559
Operations Cost ($/Mile)	$0.79	$0.80	$0.83	$0.84
Total Costs:	**$721,321**	**$677,090**	**$689,735**	**$908,193**
Lifecycle Cost:	**72,132,087**	**67,709,015**	**68,970,581**	**90,819,202**
Lifecycle Cost ($/Mile):	**$1.624**	**$1.525**	**$1.553**	**$2.045**

A more conservative estimate of future year bus price could be determined based on the current estimates and costs incurred at demonstration sites. With a 2005 average price of $3.27 million and a 2010 estimate of $2.5 million, a year 2015 conservative estimate of $1.9 million can be reached, assuming a constant reduction in purchase price based on continued maturation of the technology. Using this logic, however, it would likely take another 14 to 18 years for the price of hydrogen buses to reach that of standard diesel buses, and this does not consider that improvements in mass production of hydrogen buses will occur. Assuming mass production and technological improvements occur, the price estimate established by MARCON-DDM HIT [3] is possible.

From the information provided here, it can be seen that the capital costs associated with hydrogen-fueled buses is the largest expense. However, as shown in Table 6 and Table 7 operational costs at demonstration sites were also larger than those for typical transit buses. AC Transit reported an operational of $1.85/mile for the hydrogen fuel cell buses. SunLine Transit Agency reported a cost of $1.55/mile for fuel cell buses and a cost of $2.44/mile for the internal combustion engine buses. Operational costs at Santa Clara VTA were significantly higher, at $6.46/mile, due to higher fuel costs (hydrogen delivered to site) as well as higher maintenance costs.

Table 6. Hydrogen Bus Operation Costs ($/Mile)

Demonstration Site	AC Transit	SunLine Transit Agency		Santa Clara VTA
No. Hydrogen Buses	3	1	1	3
Bus Type	Fuel Cell	Fuel Cell	HHICE	Fuel Cell
Manufacturer	Van Hool	Van Hool	New Flyer	Gillig
Fuel Cost	1.28	1.11	1.85	2.91
Maintenance Cost	0.57	0.44	0.59	3.55
Total Operation Cost	**1.85**	**1.55**	**2.44**	**6.46**

Table 7. Annual Hydrogen Bus Operation Costs

Demonstration Site	AC Transit	SunLine Transit Agency		Santa Clara VTA
No. Hydrogen Buses	3	1	1	3
Bus Type	Fuel Cell	Fuel Cell	HHICE	Fuel Cell
Manufacturer	Van Hool	Van Hool	New Flyer	Gillig
Total Fuel Cost	$79,604.48	$56,533.41	$78,667.55	$117,005.28
Annual Fuel Cost	$45,488.27	$25,125.96	$34,963.36	$82,591.96
Total Maintenance	$35,114.59	$22,132.10	$25,652.26	$143,528.18
Annual Maintenance	$20,065.48	$9,836.49	$11,401.00	$101,314.01
Total Annual Operational Costs	**$65,553.75**	**$34,962.45**	**$46,364.36**	**$183,905.97**
Annual Operation Cost/Bus	**$21,851.25**	**$34,962.45**	**$46,364.36**	**$61,301.99**

Table 5 shows typical operational costs associated with CNG, ultra low sulfur diesel (ULSD), biodiesel (B20), and diesel-electric hybrid buses. Operational Costs per mile for these bus types ranges between $0.79/mile and $0.84/mile, much less than that reported for hydrogen buses. However, it should be noted that the maturity of these technologies compared to hydrogen is much greater, and maintenance expenditures are lower.

As shown, the capital costs for hydrogen-fueled buses have decreased by approximately 24% in relatively short span of time. It could be expected that operational costs may also decrease as the technology matures. MARCON-DDM HIT [3] shows expected annual maintenance costs of $42,422 for hydrogen fuel cell buses in 2015, compared to an estimated $50,000 in maintenance costs for diesel buses in 2015. This indicates a possible future year scenario where hydrogen bus capital costs and annual maintenance costs rival those of standard transit diesel buses.

In addition to the costs associated with hydrogen-fueled buses themselves, costs related to the support infrastructure must also be considered. This includes maintenance and refueling facility upgrades that must be made to accommodate the new bus fleet. It also includes the hydrogen production facilities.

Table 8 outlines the costs reported by the demonstration sites for both the hydrogen production and dispensing station as well as the maintenance upgrades made at each site. The maintenance costs reported by AC Transit are for modifications made to an existing facility. AC Transit did not report hydrogen facility costs. The hydrogen station at Santa Clara VTA is only a dispensing station, and the cost shown above does not include the cost of delivered hydrogen. Detailed facility descriptions are provided in previous sections.

Table 8. Support Infrastructure Costs at Demonstration Sites

Demonstration Site	AC Transit	SunLine Transit Agency	Santa Clara VTA
H2 Station	-	$1,050,000	$640,000
Maintenance	$1,500,000	$50,000	$4,400,000
Total:	**$1,500,000.00**	**$1,100,000.00**	**$5,040,000.00**

A number of factors play into the cost of hydrogen production. The first of which is the method by which the hydrogen is produced. Table 9 outlines some expected costs for the production facility types considered in this report, forecourt steam methane reformation (SMR) and forecourt electrolysis. Operation costs are estimated in dollars per year, while equipment cost estimates are initial capital costs. Melendez [1] also presents some insight into hydrogen production methods based on potential production needs as well as estimated costs for each refueling station type. Melendez estimates capital costs for larger scale SMR facilities, capable of producing 1,500 to 3,000 kg/day, to be between $1.7 million and $3.5 million, with estimates for large scale electrolysis operations in that same range. In addition to the method used, the size of the hydrogen production facility needed and the cost of the resources used to generate the hydrogen itself are factors in the total cost.

Table 9. Hydrogen Production Cost Estimates by Method [26]

	Production Method		
Cost Item	SMR (100kg/Day)	SMR (300kg/Day)	Electrolysis (30kg/Day)
Equipment:	1,100,000	2,300,000	380,000
Operations:	84,000	190,000	68,000
Total Cost:	**$1,184,000**	**$2,490,000**	**$448,000**

Fuel costs experienced at demonstration sites ranged from $1.11/mile to $2.91/mile, although relatively high delivered hydrogen costs contributed to Santa Clara VTA experiencing an average of $2.91/mile. Low volume hydrogen use also contributed to high fuel cost, and increased hydrogen demand could significantly reduce these costs [17]. Expected costs at locations where hydrogen is both produced and dispensed on-site would likely be on the lower end of this range. A report by Cockroft and Owen [11] estimates fuel cost per mile for a variety of production energy sources. Those estimates range from $0.26/mile to $0.35/mile for production via a coal energy source to $1.00/mile to $1.58/mile for hydrogen production via a solar energy source, with an average production cost of $0.45/mile to $0.66/mile. These fuel costs may serve as good estimates for current year fuel costs per mile. Year 2015 fuel costs are estimated at $0.54/mile to $0.93/mile depending on production method and energy source [3].

Insight into year 2015 facility costs is also given by MARCON-DDM HIT [3]. Required maintenance facility upgrades are estimated to cost approximately $1.97 million for a fleet of 250 buses. For a medium sized transit agency, this would mean an investment of approximately $780,000 to $1.03 million for upgrades. The expense of constructing a new maintenance facility is estimated to be $1.3 million more than the cost of upgrading existing facilities for a large fleet size. Applying this to a medium sized transit fleet, the expected additional costs of constructing new facilities would be between $520,000 and $685,000. For a medium sized transit agency, the total future year cost of constructing new maintenance facilities is estimated at $1.3 million to $1.7 million.

In addition to these costs, some costs would be incurred for training. Details on training requirements that would be necessary for the transit agency have previously are outlined in Section 3.3. Many of these costs would be recurring, as some level of training, such as basic safety training, would be necessary for all employees on a yearly basis; and more specialized training, such as training in electrical systems or specialized mechanical training, would likely be necessary for each new employee working in those areas.

3. KNOXVILLE AREA TRANSIT HYDROGEN INFRASTRUCTURE REQUIREMENTS

The city of Knoxville, Tennessee, is located in Eastern Tennessee and has a population of approximately 180,000. Transit service in Knoxville is operated by KAT on 25 fixed bus routes plus three express routes and services provided for the University of Tennessee. Approximately 3.2 million people use KAT services each year. The KAT agency operates 93 buses and vans in its transit system as well as some other specialized service vehicles, which are not considered in this analysis. KAT designates 17 buses and three propane vans to provide service to the University of Tennessee. The composition of KAT's operating fleet, including buses, trolleys, and service vans, is shown in Table 10. A detailed summary of KAT's transit fleet can be found in Appendix C. KAT provides service on weekdays from 5:30 AM to 12:30 AM, a total of 19 hours of operation.

Table 10. Knoxville Area Transit Bus Fleet

Total KAT Bus System:		**KAT Buses Serving UT System:**		
Number	**Type**	**Number**	**Type**	**Route**
18	ADA Lift Vans	7	35 - 40ft Buses	East - West
27	Propane-Powered Neighborhood Service Vans	2	30ft Buses	North - South
8	Trolley Vehicles	4	30ft Buses	Ag Express
20	30ft Low Floor Buses	2	35 - 40ft Buses	Off-Campus Housing
30	35ft Buses (Low Floor and Step-up)	3	Propane-Powered Vans	Access/Link
16	40ft Buses	2	30 - 35ft Buses	Late Nite Shuttle

3.1 TRANSIT FLEET SIZE

Medium sized transit agencies wishing to convert their bus fleet to operation using hydrogen fuel will need to consider the current performance and reliability of hydrogen-fueled buses relative to their current fleet. Data collected in demonstration projects shows that with hydrogen technology in its current state an increase in fleet size will be necessary for conversion to hydrogen fuel buses. The average availability for the hydrogen-fueled buses, as experienced by demonstration sites, is approximately 60 percent. This reduction is partially due to various problems encountered with the new technology, such as issues with batteries and fuel cell stack change outs. There is also a reduction in passenger capacity based on the current technologies and hydrogen bus layouts. Transit systems that are capacity constrained and operating on a demand-based bus schedule may require additional hydrogen-buses to accommodate for a loss in passenger capacity in addition to the increase in fleet size for reliability requirements.

Based on these statistics, current fleet sizes must increase by a multiple of 42% to achieve a desired average availability of 85 percent, assuming no additional increase in service requirements are planned. The requirement of 85 percent availability applies to each bus and indicates that an availability of 85 percent is required to maintain service demands. Fleet size calculations for the KAT bus fleet are based on a required average availability of 85 percent. A simplified estimation of fleet size based current and desired availability levels is calculated as follow:

$$N = 1.42C(1+X) \qquad (eq.\ 1)$$

Where *C* is the size of the transit agency's current bus fleet, *X* is the planned fleet size expansion for the given time frame in percent, and *N* is the number of new hydrogen buses required. This assumes a one-to-one bus replacement strategy based on average availability. Other sources, however, indicate that improvements to fuel cell technology and fuel cell bus designs will improve over the next few years. One source indicates that fuel cell buses will have the same operating capabilities as standard buses by 2015 [3]. As fuel cell technology improves, this may very likely be the case; however, until such successes can be proven, possibly through future demonstration projects, transit agencies should consider additional hydrogen fuel cell buses to meet their needs. Since fleet conversion is likely to be phased over a period of time, observations of bus performance can easily be made, which could justify reducing the number of fuel cell buses required to meet the same level of service.

Using equation 1, fleet size requirements for KAT can be calculated. Although a need for expanded KAT services has been identified, due to the current economic situation, the KAT is currently in a conservative growth mode and the Knoxville Regional Transportation Planning Organization long range plan assumes a no growth scenario for KAT, according to the 2009 - 2034 Knoxville Regional Mobility Plan [27]. Therefore, to complete the transition to hydrogen fuel, the KAT bus fleet would need to expand to 132 hydrogen fuel cell buses. However, since it is expected that KAT fleet conversion will occur in phases, this number could be significantly reduced, potentially down to the current fleet size, based on future technology improvements.

3.2 PRODUCTION AND STORAGE FACILITIES

Hydrogen production and storage requirement estimations assume that KAT buses operate similar route lengths and average daily miles traveled to that of the demonstration sites. It also assumes that hydrogen fuel dispensers can serve two buses simultaneously as was the case at the AC Transit facility as opposed to only having the capability to fuel one bus at a time. Lastly, it is assumed that refueling operations occur at periods staggered throughout the day, although it may be more likely that refueling occurs only during specific periods either before or after buses enter or exit service.

Hydrogen production costs for Knoxville range from $4.18 - 4.82/kg for natural gas reformation and $6.64 - 6.66/kg for electrolysis, based on the HyDRA model [18]. Considering average fuel economies, hydrogen fuel would cost between $0.03 per mile and $0.15 per mile more than diesel counterparts for production by natural gas reformation in Knoxville. Production by electrolysis would bring hydrogen fuel costs to approximately $0.54 per mile greater than diesel costs. Natural gas reformation is currently much more economical for hydrogen production to serve the KAT fleet. It should still be noted that demand for hydrogen on-site will have influence over the production costs and that special rates with electricity and gas providers may be reached to reduce these costs further.

Among the three demonstration sites, a total of 65 service-months were observed, in which a total 1,918 re-fueling operations were completed. Each demonstration bus was refilled on average every three days. The KAT currently operates 93 buses in its fleet. Although fleet conversion is expected to occur in phases, total conversion under present conditions would require 132 buses (see section 3.1). Also considered here is the option that first converts only the sub-system of buses that serve the University of Tennessee campus to provide an example of the needs to service a smaller number of fleet vehicles.

Based on the assumptions made for this case study, hydrogen storage and dispensing requirements for KAT are calculated. Table 11 outlines estimated storage capacity needs at KAT. For maximum demand conditions, the daily production and storage capacity would need to be nearly 1200kg per day based on average fill amounts and typical refueling schedule. For a smaller number of hydrogen-fueled buses, this capacity could be significantly reduced. For the case that hydrogen fuel cell and bus technology will mature as expected, it could be assumed that the total daily production and storage capacity required is only 835kg based on the reduction in transit vehicles required. The estimated number of fills per day is calculated based on average mileage per day and the current fuel economy performance.

Table 11. Estimated Storage and Dispensing Requirements

	Current	Max	UT System
KAT Bus Fleet	93	132	17
Storage Capacity Needed (kg)	835	1184	153
Number of Fills/Day	36	51	7
Time Refueling/Day (minutes)	278	394	51

Based on average fill times, the number of hydrogen refueling stations is calculated to achieve required service levels under different scenarios. Requirements for KAT are shown in Table 12. Using only one dispenser would result in an average daily refueling time of up to 6.6 hours for the entire fleet assuming a fleet size increase to 132 buses. A scenario reducing the required number of hydrogen-fueled buses to the current number of 93 buses would require 4.6 hours per day for refueling with only one dispenser. By varying the number of dispensers available on-site, the total refueling time can be significantly reduced. As shown here, increasing the number of fuel dispensers on-site to three can reduce the total refueling time to just over two hours. This is much more reasonable and could be completed in off-peak periods to reduce delays in service throughout the day.

Table 12. Hydrogen Fuel Dispensers Required to Reduce Fill Time per Day

	Hours/Day of Refueling		
Number of Dispensers:	**Current**	**Max**	**UT System**
1 Dispenser	4.6	6.6	0.8
2 Dispensers	2.3	3.3	0.4
3 Dispensers	1.5	2.2	0.3

3.3 FACILITIES AND PERSONNEL

For the conversion to hydrogen buses, KAT facilities will need to be overhauled to allow for the safe use of hydrogen fuel. Service bays and refueling facilities are configured for maintaining and operating KAT's current bus fleet, which consists of gasoline-, diesel-, and propane-fueled vehicles. The refueling facilities at KAT consist of one service bay with gasoline and diesel fuel pumps as well as one propane refueling station. The gasoline and diesel refueling bay is also equipped with revenue collection equipment and bus washing machines. KAT operates one maintenance shop, which is equipped with 12 service bays, and the maintenance staff operates several pieces of specialized equipment, which would not be safe in the vicinity of hydrogen-fueled buses. Based the extent of upgrades required, the construction of new, separate facilities for maintenance, refueling, and washing operations for hydrogen-fueled buses is recommended.

Based on fleet size calculations and given that KAT facilities are currently approaching capacity to service their existing fleet, an increased number of maintenance service bays will be required. Using current reliability levels, it can be estimated that 17 service bays will be required, or one additional service bay per 8 added vehicles. Still, with fleet conversion most likely occurring in phases, this number of service bays may not be necessary as reliability increases. A phased construction and conversion of maintenance facilities would be recommended to compliment the phased transition.

These new facilities would need to incorporate various safety measures to ensure safe operations. The following are some recommended practices for refueling facilities, maintenance facilities, and wash facilities to support hydrogen-fueled bus fleets [15-17]:

- All facilities including refueling facilities, maintenance facilities, and wash facilities should be equipped with hydrogen detectors capable of accurately determining the percent volume of hydrogen in air.
- All facilities including refueling facilities, maintenance facilities, and wash facilities should be equipped with flame sensors to alert of any fire which begin as a result of a leak. Facilities should also be equipped with an appropriate fire suppression system to quickly extinguish any fire.
- All facilities including refueling facilities, maintenance facilities, and wash facilities should have an appropriate ventilation system capable of safely and quickly clearing the air in the facility of any leaked hydrogen. The type of ventilation system may be dependent on the type of facility constructed.
- All facilities including refueling facilities, maintenance facilities, and wash facilities shall incorporate an anti-static coating on floors and doorways so as to prevent any static buildup which could trigger a fire in the event of a hydrogen leak.
- All facilities including refueling facilities, maintenance facilities, and wash facilities should be equipped with an appropriate alarm system, which is connected to both the hydrogen detectors and flame sensors, to properly alert necessary personnel of any issues.
- Alert levels shall be based on the percent of the lower flammability limit for hydrogen in air. The recommended level for the initial warning is 15% lower flammability limit, at which necessary precautions should be taken to safely vent and leaked hydrogen out of

the room or area. The recommended level for the second warning is 40% lower flammability limit, at which all non-emergency electrical systems should be shut off and the area should be evacuated immediately.

- Hydrogen dispensing stations should be equipped with an emergency stop button to shut off any flow of hydrogen during a potential leak.
- Doorways at all facilities including refueling facilities, maintenance facilities, and wash facilities should be designed to automatically open in the event of detected leak.
- Ventilation systems should be connected to the alarm system in the facility and should automatically turn on upon the detection of any hydrogen leak.
- All tools and equipment including any heating equipment used within the facilities should be non-sparking and ignition free to prevent the likelihood of a fire caused by the operation of such equipment.
- For maintenance facilities modified from existing facilities, a fire wall shall be installed to prevent any fire from spreading to other locations within the facility.
- For maintenance facilities modified from existing facilities, purging of hydrogen fuel may be required to meet local or state regulations.
- Lighting and electrical systems shall meet any local or state classification regulations.
- Any control panels used with a facility shall have a nitrogen purge system or another appropriate system for restricting hydrogen from coming in contact with the electrical systems.

Training for personnel performing maintenance, refueling, and other procedures is also vital. Because of the amount of training required, many demonstration sites receive on-site technical assistance from technology manufacturers to assist employees with the transition, with transit agency crews successfully taking over responsibilities in the absence of this support [23]. At AC Transit, an agreement with Chevron places them in responsibility of all maintenance and operations at the hydrogen station for two years [15]. At Santa Clara VTA mechanics received training from Ballard on the hydrogen fuel cell and propulsion systems and training from Air Products on the hydrogen dispensing station, and Ballard placed one mechanic on-site for the project [16]. Additional training at Santa Clara VTA was provided to other groups who operate or perform maintenance on the hydrogen-fueled buses [16]. While some technical training assistance may be available through manufacturers, transit agencies will likely need to agency employees for maintenance and operations procedures. Some recommended training practices are provided by MARCON-DDM HIT [3]

KAT employs a number of people in a variety of positions, which will require additional training and qualifications appropriate for the hydrogen fuel bus fleet. This includes all personnel involved in maintenance and operations tasks including managers and supervisors. In addition, KAT employs 141 bus, trolley, and van operators plus 30 University of Tennessee bus operators who would need at least a minimal level of training on operations and troubleshooting for the fuel cell systems. The KAT maintenance department, alone, consists of 45 employees, including 21 mechanics and a number of other service employees, who will need extensive training and specialized rehiring to meet the demands of new technology. Additional training in electrical systems or an increase in the number of electricians may be necessary to efficiently maintain the new bus fleet. Furthermore, extensive and continuous training for first responders should be conducted. One approach used by many agencies involved in demonstration projects was to develop instructional videos that could be used for such training [23].

3.4 IDENTIFICATION OF HYDROGEN REFUELING FACILITY REQUIREMENTS

Best Practices for Hydrogen Refueling Station Location

Many considerations for the placement of hydrogen refueling facilities have been identified in Section 2.4. With these considerations in mind, the following is a list of recommended best practices to be incorporated into determining hydrogen refueling station locations for stations serving public transit agencies:

- Hydrogen refueling facilities should be located in such a manner as to provide adequate and convenient refueling service for hydrogen-fueled bus fleets. Since it is expected that the range of hydrogen-fueled buses will be less than that of standard diesel buses, facility location should be central to the bus routes in operation to provide optimum service to those routes and less deviation from those routes.
- Hydrogen refueling stations that serve public transit agencies should be located in a manner which provides a high degree of visibility to the public to help increase awareness and promote interest in hydrogen technology.
- To provide a means to transition into a widespread adoption of hydrogen technology, these hydrogen refueling stations should be accessible by the general public. However, for safety purposes stations should still be staffed and operated by properly trained personnel as described in previous reports.
- Since future networks of hydrogen refueling stations are likely to rely on stations located along major interstates and highways, hydrogen refueling stations should be located near major highway and interstate systems.
- Locating hydrogen refueling stations within residential neighborhoods should be avoided if possible; however, construction of stations in strategic locations that are visible to local residents is recommended. Since income and social status have been identified as major factors in the decision to purchase a hydrogen-fueled vehicle, visibility and advertisements should target residential areas that have a higher household income.
- Public awareness programs should be initiated to educate local residents and businesses about the refueling station and the use of hydrogen as fuel.
- In order to promote support of hydrogen facilities among local residents and businesses, the public awareness programs should be initiated early in the planning process, and meetings should be held often to maintain support and to address any arising concerns.

Suggested Locations for KAT Refueling Facilities

Refueling operations at KAT currently occur at one central facility, and refueling operations are typically done every night as the buses in operation return to the main facility. With the transition to hydrogen-fueled buses, there are some concerns over possible decreases in range and refueling needs. Hydrogen refueling facilities need to be located in a position that gives easy access to hydrogen-fueled buses throughout the day without significant diversion from their bus routes. Following this logic, as well as the recommended practices outlined above, potential strategic locations for the placement of a hydrogen refueling station can be determined.

A geographic information systems (GIS) model of Knox County, Tennessee, was developed based on U.S. Census Bureau 2008 TIGER shapefiles [28] for the area using ArcGIS 9.0 (see Figure 1). Specifically, the model includes the street network, railroads, hydrology, and U.S. Census blocks which contain information on population demographics. These shapefiles were used to generate individual link and node layers for each feature type, which were then used to build the following GIS model for analysis.

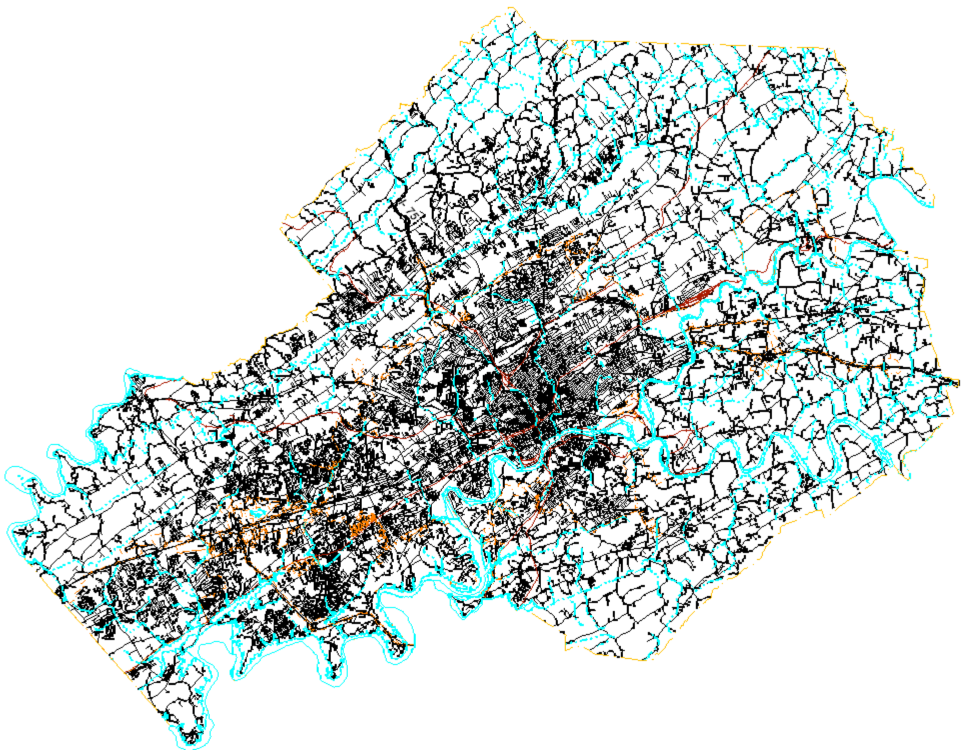

Figure 1. Model of Knox County Road Network

Using this as a base for the model, additional layers were created to represent KAT bus routes. Road segments, which are used in the current bus route system, were selected from the line layer. Those segments were then exported to create a separate layer containing only those line segments. This process was done for both the entire KAT system and the system specifically serving the University of Tennessee, as it may become important to initially focus on the routes serving the University. Figure 2, below, shows the KAT bus route system used for analysis.

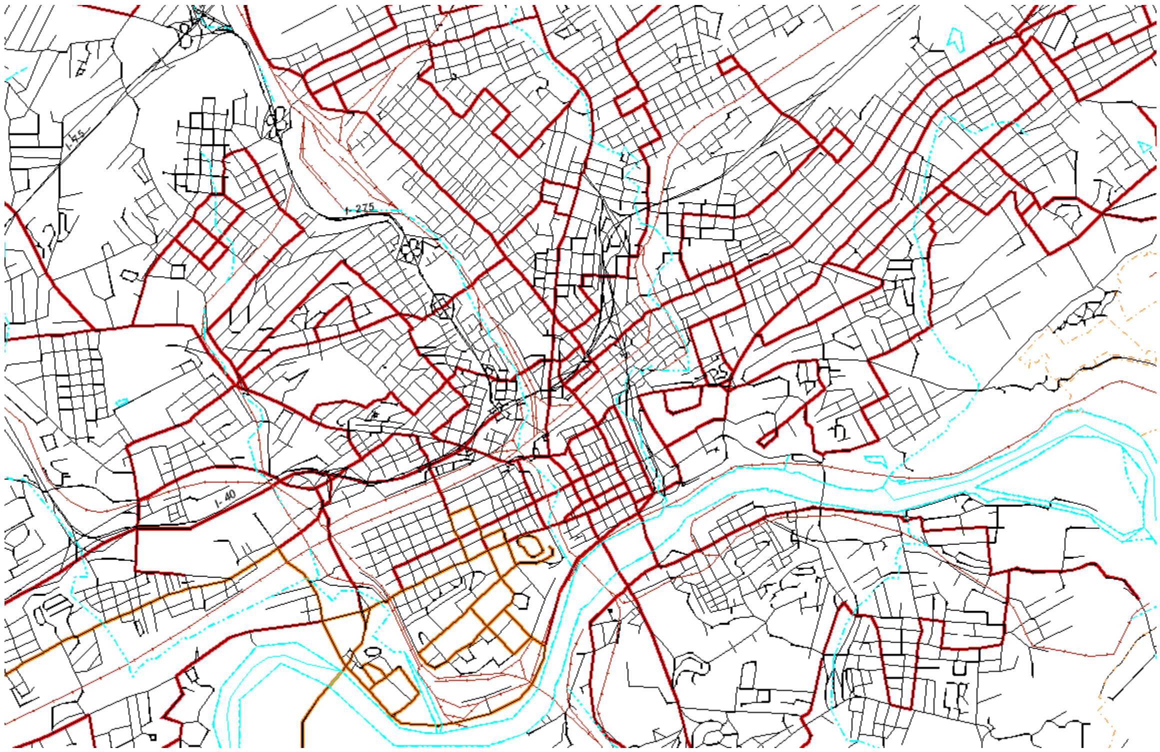

Figure 2. The KAT Bus Route System

Lines representing the current interstate system, including I-40, I-75, and I-275, in Knox County and entrance and exit ramps serving the interstate system were extracted. These line types were selected because of the high amount of traffic which uses the interstate system on a daily basis. The entrance and exit ramps are of further importance because they represent points where users of the interstate system could potentially access a hydrogen refueling station located on the local road network.

Using these layers a series of buffers are created based on reasonable offset distances from selected features. Here, access from the KAT bus system is of great importance. Buffers were created following all KAT bus routes at a width of 0.1 miles to either side of the bus routes. Figure 3 depicts these buffers built around the bus system. This buffer size will allow for the identification of areas which lay immediately next to roadways which are part of the KAT bus route system. Also, of importance is proximity to and visibility from the interstate system since a potential future network of hydrogen refueling stations will likely rely on hydrogen refueling stations located on or near the existing interstate system. Half-mile buffers were constructed around interstate entrance and exit ramps to identify these locations. Half-mile buffers were also created around the interstate system itself. Figure 4 shows buffer zones constructed around the interstate system.

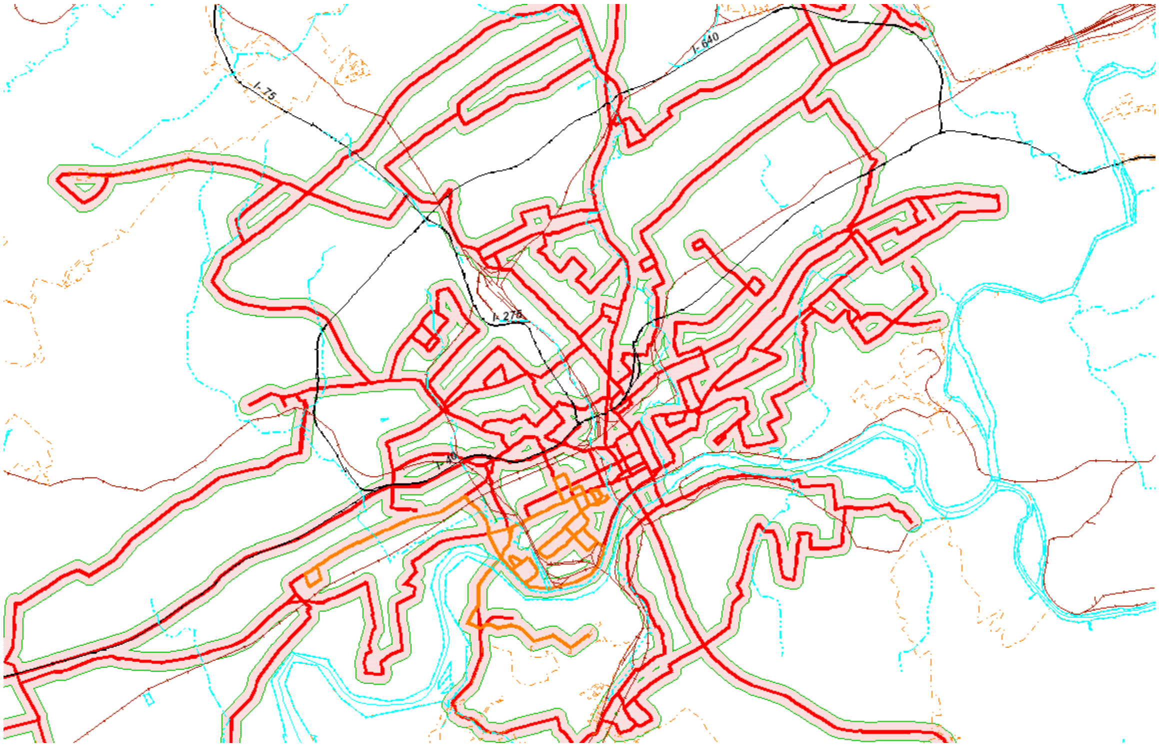

Figure 3. Buffers Constructed around KAT Bus Routes

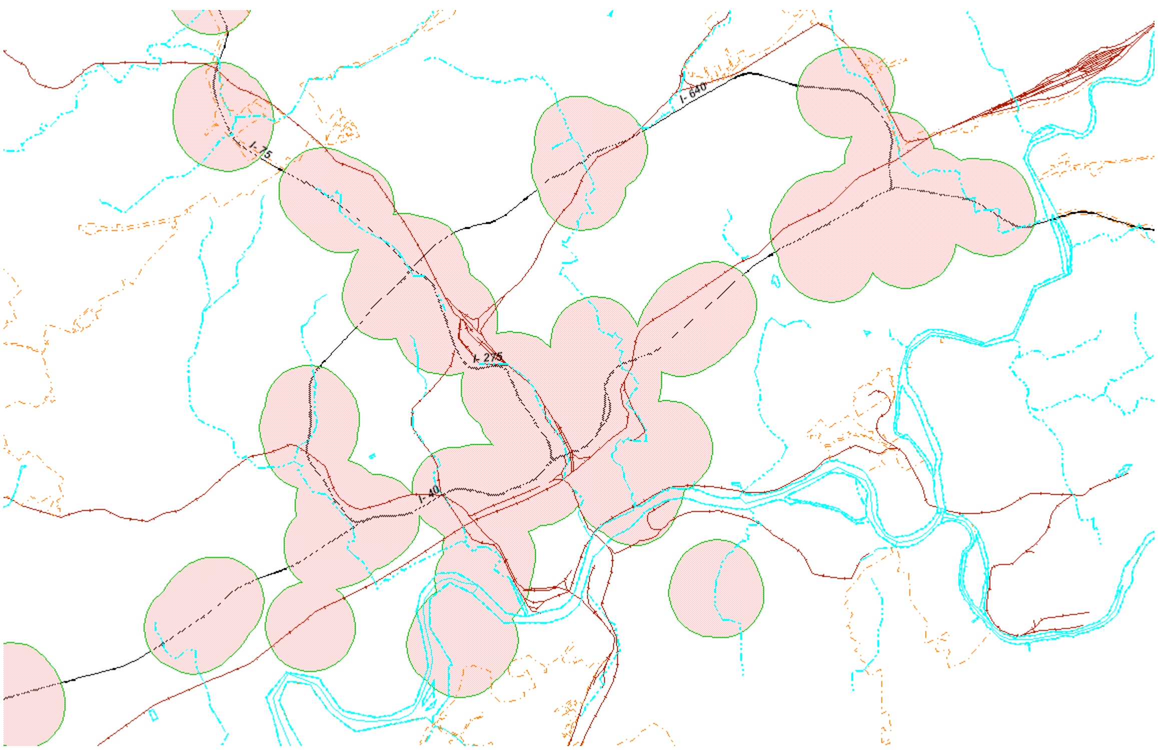

Figure 4. Half-mile Buffer Zones Around Interstate Exits

Yet another consideration is the proximity to the downtown business district. For the current KAT bus system, almost all bus routes pass by or originate from the City County Building on Main Street. Furthermore, almost all routes utilize either Main Street, Cumberland Avenue, Gay Street, Locust Street, Summit Hill Drive or some combination of these roads within the downtown area. Considering the heavy use of these roads under the current bus route system, proximity to this area is useful in helping to maintain the current level of bus service. A series of buffers can be created around the downtown area identifying locations within 0.5 miles, 1 mile, 1.5 miles, and 2 miles. These buffers are shown in Figure 5.

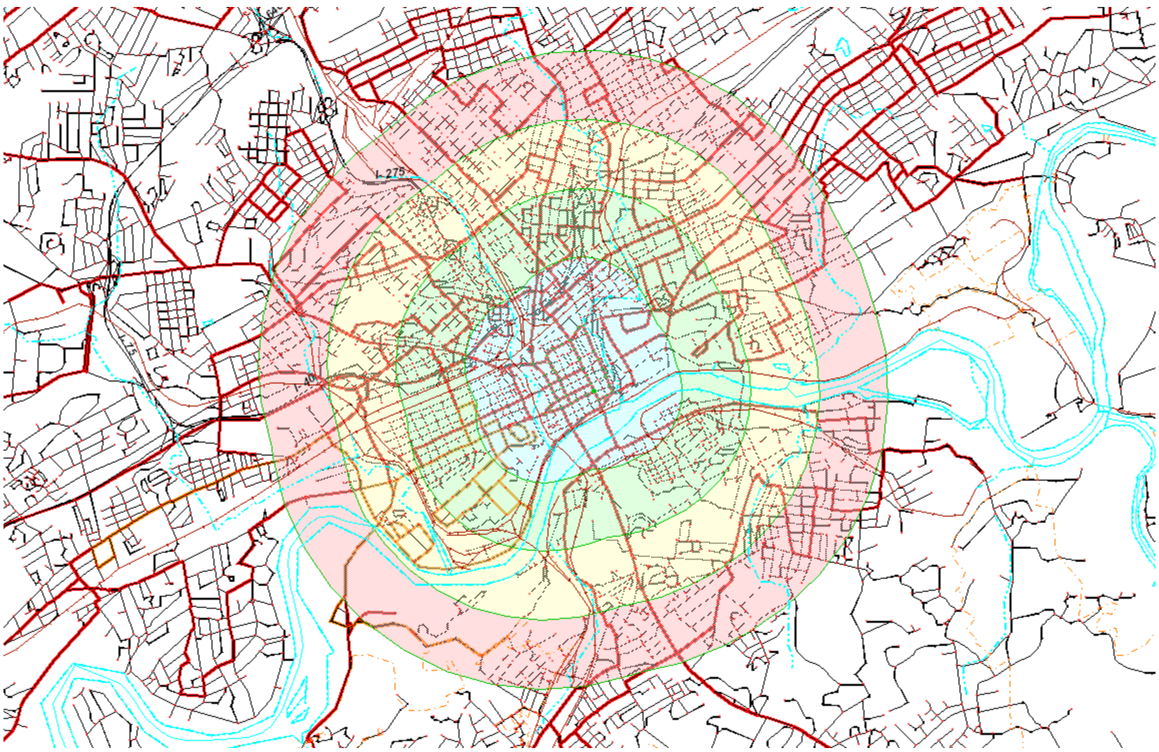

Figure 5. Buffer Zones Constructed around the Downtown Business District

Using these buffers, a number of strategic locations can be identified based locations where the buffers intersect. Based on the buffers created around the interstate ramps, a selection of links contained within the KAT bus route system are created. Then, using only these selected links, another set can be created based on location within the buffer zone near the downtown business district. The selection can be further narrowed by creating a set from these links that are located within the interstate buffer zone. In this case, this set eliminates some links that are located near ramps but are outside the half-mile buffer of the interstate itself. Finally, this set of links, and the buffers off of them, can be compared again to the downtown business district to determine sites with optimal characteristics. Figure 6 shows these locations identified as strategic for placement of hydrogen refueling facilities.

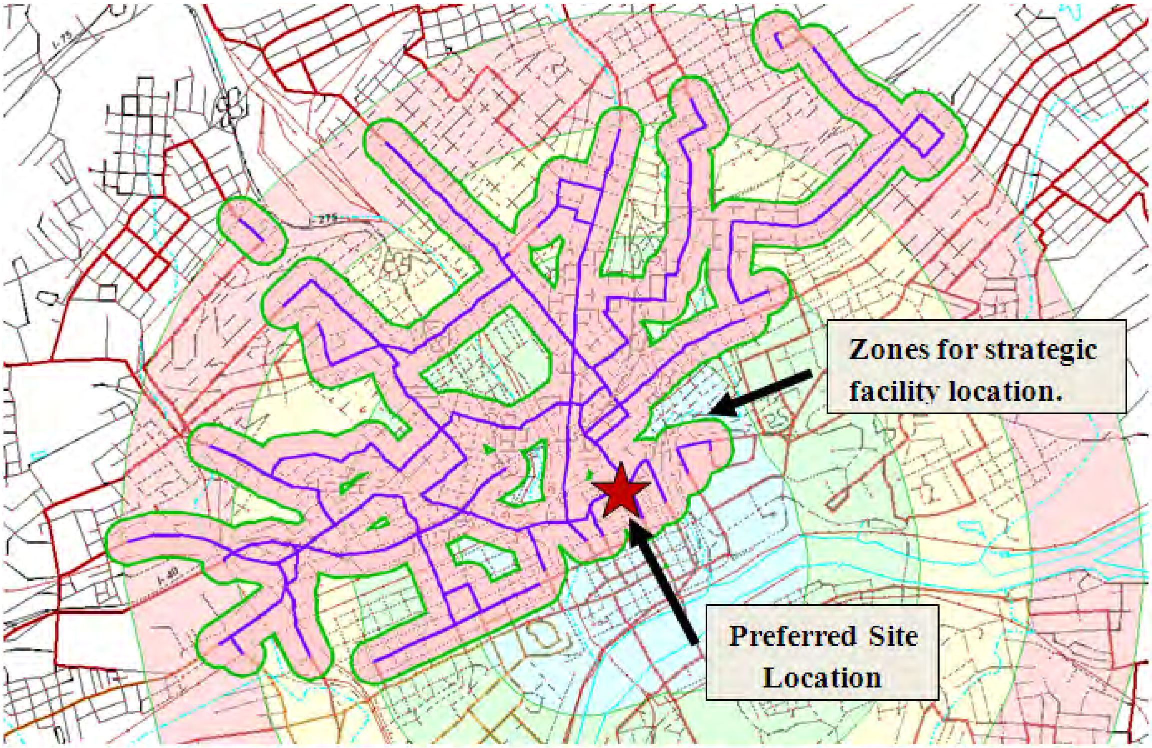

Figure 6. Zones Identified for Strategic Location of Refueling Facilities

It should be noted that this model does not identify individual parcels for station locations, only general locations or zones which meet the requirements outlined above. Further analysis within these zones can be done to determine parcel information and select individual parcels for locating the refueling station. Other GIS models, such as the one provided by KGIS[1] may be utilized to further specify parcel information.

As an additional measure of effectiveness, the approximate number of residents within a given range of the hydrogen refueling site location is determined. For the sites identified here, approximately 188,485 residents of Knox County live within a five mile radius. Approximately 328,951 Knox County residents, as well as some residents of neighboring counties which are not accounted for here, live within a ten mile radius of these sites. This represents approximately 49% of the population of Knox County within a five mile radius and approximately 86% of the population of Knox County within a ten mile radius.

3.5 TRANSITION STRATEGIES FOR HYDROGEN CONVERSION

A number of issues have been investigated that are important to the transition of a transit bus fleet to hydrogen fuel. For a complete transition, an increased number of buses will be required. New maintenance and refueling facilities will be necessary to adequately serve the new buses and to address new safety concerns with the new technology. Also, to operate with hydrogen

[1] http://www.kgis.org/Portal/Default.aspx

fuel, adequate infrastructure for producing and storing hydrogen fuel is needed. Due to the high capital costs involved with each of these aspects, a transition to hydrogen is not likely to occur in the short-term. Additionally, the cost involved to operate the buses increases as buses age. As shown by Simms [28], the operating cost per kilometer can nearly triple over the life of the bus. Replacing all, or even a large number of buses, at one time would result in overwhelming costs to the transit agency as the bus fleet ages. A phased acquisition of buses and infrastructure would better serve the transit agency.

A number of alternatives for phased development of supporting infrastructure may be considered for a transit agency converting to hydrogen-fueled buses. One alternative to consider is the use of excess hydrogen, hydrogen not used as fuel for the transit fleet, to generate electricity. This method would allow for complete initial construction of hydrogen production and storage facilities, while also allowing for a phased acquisition of hydrogen-fueled buses. In the case of KAT, this would likely be cost prohibitive and inefficient.

A second alternative may be to begin the transition by converting high visibility bus routes first. Beginning with a smaller number of hydrogen buses and facilities would reduce initial costs and allow for a gradual acquisition of hydrogen buses. It would also serve to promote the technology to the general public before full-scale adoption of the technology by the transit agency. These could be routes serving the most users, which are located in strategic locations for publicly available infrastructure, such as along major highways. This strategy could also allow for smaller scale initial facilities construction. Initial construction of facilities to serve only these routes would reduce capital costs associated with hydrogen production and storage facilities as well as the reduce the initial requirements for maintenance and service facilities. Such a measure also allows for alternative methods to be utilized for hydrogen production. Electrolysis using renewable energy sources such as solar power could be beneficial as it would allow for production stations to be more spatially distributed and potentially smaller in scale to serve more localized needs.

Another alternative would be to incorporate engine technology into the phasing strategy. Two alternative technologies have been identified as viable alternatives, fuel cells and internal combustion engine. Based on maturity of the technology and current costs, hydrogen internal combustion engine technology has been identified as a favorable early choice for propulsion technology. Fuel cell technology, on the other hand, is expected to continue to evolve and decrease in cost over the coming years, making it a more competitive option in the future. Thus, one option may be to use lower-cost internal combustion engine technology in initial investments and to gradually shift to fuel cell technology over time. A challenge with this strategy is developing the resources to manage two states of hydrogen fuel, liquid and gas. Another major downfall to this strategy is that the differing technologies involve very different components and could present problems in maintenance and operations, particularly for smaller and medium sized transit operations with limited personnel. SunLine Transit Agency, which operated both fuel cell and internal combustion engine buses during its demonstration project, experienced higher maintenance and total operating costs per mile for the internal combustion engine buses than for the fuel cell buses [15], and it is expected that as the technology matures these costs will reduce even further for fuel cell buses to a level equivalent or better than those of diesel buses [3]. Still, given recent experiences, it may be preferable for some agencies to initially replace older or out-of-service buses with new buses operating with hydrogen internal combustion engines.

A number of KAT's bus routes are highly visible and accessible to the general public. Routes such as these would be excellent candidates for an initial conversion to hydrogen-fueled buses. Specifically, routes serving the University of Tennessee would provide optimum visibility to a large portion of the general public, and smaller scale hydrogen production and servicing facilities could adequately service this system. As more buses became eligible for replacement, this could be expanded to other routes, beginning first with other high visibility corridors serving the university.

KAT's bus replacement strategy is based on guidelines from the Federal Transit Administration and attempts to achieve an average bus age of six years. Most KAT buses are considered heavy duty and would thus be eligible for replacement under FTA minimum useful life requirements after 12 years or 500,000 miles, whichever comes first. KAT also operates some medium-duty buses, which are eligible for replacement after 10 years or 350,000 miles. KAT's current fleet has not always followed this replacement strategy and has, at some points, purchased large quantities of buses at a single time. This strategy can lead to significant maintenance and operations issues as the fleet ages and many buses simultaneously become obsolete.

The age of KAT's bus fleet is represented in Table 13. It should be noted that the fleet age data provided by KAT only includes 90 buses, not 93 as previously noted. The three additional buses which were not included in this data were assumed to have an age greater than 12 years and are, thus eligible for replacement. Based on KAT's replacement procedures, an average of nearly eight buses should be eligible for replacement at the end of each year. Based on that estimate, an average of 11 hydrogen buses would be required each year to replace the current buses, assuming current technology. However, as KAT has a large number of buses which are of age beyond their expected service life, maintaining this type of strategy would require the use of some buses beyond a 12 year service life.

Table 13. Age of the Current KAT Bus Fleet

Age (years):	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11	11 - 12	> 12
# Buses (Estimated)	7.75	7.75	7.75	7.75	7.75	7.75	7.75	7.75	7.75	7.75	7.75	7.75	0
# Buses (Actual)	0	9	0	6	3	5	14	14	11	0	0	8	**23**

3.6 COSTS AND TIMELINE FOR TRANSITION TO HYDROGEN TECHNOLOGY

An estimated maximum 132 new hydrogen fuel cell buses would be needed for KAT to make a complete transition to hydrogen fuel. As hydrogen bus technologies and production methods improve, however, it is expected that that number will reduce to the current bus fleet size of 93. Facility requirements to support a fleet of this size were also estimated. A hydrogen production/storage capacity of approximately 835kg was estimated for the current fleet size, while approximately 1200kg capacity was estimated for the maximum fleet requirement scenario. Using these estimates and the cost estimates above, costs can be estimated for a total transition, assuming conversion begins in year 2015 or after. These cost estimates are summarized in Table 14, below, with Case 1 assuming no increase in fleet size required and Case 2 assuming a fleet increase to 132 buses is required.

Table 14. Estimated Yearly KAT Costs

	Case 1	Case 2
Total Fleet Size	93	132
New H2 Buses (avg.)	8	11
Facilities Costs		
Maintenance Facilities	$1,300,000	$1,700,000
H2 Production Facilities	$969,157	$1,392,800
Annual Costs		
H2 Production	$528,833	$760,000
Bus Purchase	$7,618,048	$10,474,816
Bus Operations (per additional buses)	$314,975	$433,091

Based on KAT's current bus replacement guidelines, an average of eight buses are eligible for replacement at the end of any year. Section 3.5 details the transition strategy for hydrogen conversion. In analyzing the costs associated with such a transition, three cases will be considered. Case 1 considers no increase in fleet size is necessary. Case 2 considers that an increase in fleet size is required due to reductions in performance and reliability in transitioning to hydrogen-fueled buses, and Case 3 considers that increases in fleet size are only necessary during the initial years of fleet conversion. Costs are not discounted and bus purchase price estimates are held constant across the transition period, as estimates have not been made for years beyond the 2015 scenario.

Table 15 outlines the annual costs associated with each of these scenarios. For Case 1, initial year costs are $10,362,433 based on construction of new facilities and purchase of hydrogen buses to replace those existing buses eligible for replacement. Case 2 and Case 3 have higher initial year costs due to increased facility needs as well as increased requirement for hydrogen buses. This method approximates the total transition cost for Case 1 to be approximately $96.6 million, $136.9 million for Case 2, and $116.6 million for Case 3. Once total conversion is achieved, the yearly costs will only be those required to replace aging buses as well as the costs of maintenance and operations.

Table 15. Approximate Annual Costs for KAT Conversion

KAT Hydrogen Conversion - Case 1: No Increase in Fleet Size Required in Transition

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Replace (Old)	8	8	8	7	8	8	8	7	8	8	8	7
Acquire (New)	8	8	8	7	8	8	8	7	8	8	8	7
Costs:												
Facilities	2,269,157	0	0	0	0	0	0	0	0	0	0	0
New Buses:	7,933,023	7,933,023	7,933,023	6,941,395	7,933,023	7,933,023	7,933,023	6,941,395	7,933,023	7,933,023	7,933,023	6,941,395
Total Annual Costs ($):	**10,202,180**	**7,933,023**	**7,933,023**	**6,941,395**	**7,933,023**	**7,933,023**	**7,933,023**	**6,941,395**	**7,933,023**	**7,933,023**	**7,933,023**	**6,941,395**

KAT Hydrogen Conversion - Case 2: Increase in Fleet Size to 132 Hydrogen-Fueled Buses Required

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Replace (Old)	8	8	8	7	8	8	8	7	8	8	8	7
Acquire (New)	11	11	11	11	11	11	11	11	11	11	11	11
Costs:												
Facilities	3,092,800	0	0	0	0	0	0	0	0	0	0	0
New Buses:	10,907,907	10,907,907	10,907,907	10,907,907	10,907,907	10,907,907	10,907,907	10,907,907	10,907,907	10,907,907	10,907,907	10,907,907
Total Annual Costs ($):	**14,000,707**	**10,907,907**	**10,907,907**	**10,907,907**	**10,907,907**	**10,907,907**	**10,907,907**	**10,907,907**	**10,907,907**	**10,907,907**	**10,907,907**	**10,907,907**

KAT Hydrogen Conversion - Case 3: Additional Buses Required Only During Initial Period

Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Replace (Old)	8	8	8	7	8	8	8	7	8	8	8	7
Acquire (New)	11	11	11	11	11	11	8	7	8	8	8	7
Costs:												
Facilities	3,092,800	0	0	0	0	0	0	0	0	0	0	0
New Buses:	10,907,907	10,474,816	10,474,816	10,474,816	10,474,816	10,474,816	7,618,048	6,665,792	7,618,048	7,618,048	7,618,048	6,665,792
Total Annual Costs ($):	**14,000,707**	**10,474,816**	**10,474,816**	**10,474,816**	**10,474,816**	**10,474,816**	**7,618,048**	**6,665,792**	**7,618,048**	**7,618,048**	**7,618,048**	**6,665,792**

Table 16 and Table 17 outline the current KAT operating funds and expenses. As can be seen in Table 17, annual vehicle operations and maintenance amount to approximately $10.9 million, which is comparable to Case 2 beyond Year 0. After Year 0, Case 1 has an average yearly vehicle expense of $7.66 million, and Case 3 has an average yearly vehicle expense of $8.74 million; however, once total transition has occurred, the average yearly vehicle expense for Case 3 will also be $7.66 million. If these scenarios become reality, this will lead to an approximate reduction in operating expenses of $2.7 million; however, it is yet to be seen whether this technology will reach these level of performance. Still such a savings, if realized, could be applied to facility upgrades or to expand the current transit system.

Table 16. Summary of KAT Operating Funds [29]

Directly Generated Funds			**$2,627,800.00**
	DO Fare Revenues	1,243,600.00	
	PT Fare Revenues	0.00	
	Other Revenues	1,384,200.00	
	Dedicated and Other	0.00	
Federal Funds			**$2,706,900.00**
	UAF	1,858,200.00	
	Other Federal	848,700.00	
State Funds			**$1,983,500.00**
	General Revenue	1,983,500.00	
	Dedicated and Other	0.00	
Local Funds			**$6,508,000.00**
	General Revenue	6,328,000.00	
	Dedicated and Other	180,000.00	
Total KAT Operating Funds:			**$13,826,200.00**

Table 17. Summary of KAT Expenses [29]

Vehicle Operations	$8,573,400.00
Vehicle Maintenance	$2,354,800.00
Non-Vehicle Maintenance	$187,200.00
General Administration	$2,637,400.00
Total KAT Operating Expenses:	**$13,752,800.00**

Lastly, it should be noted that these scenarios do not include any estimates of government subsidies in the prices presented. It may be likely that government funds dedicated to developing alternative fuel infrastructure could be applied to further aid such a transition. It should also be noted that a number of technical challenges must be overcome, and with such a pioneering transition there are a number uncertainties. As seen at demonstration sites, early experience with hydrogen bus systems can involve increased maintenance costs due to inexperience. These issues may add to initial costs. Contracts for third part maintenance or hydrogen production or dispensing can also increase these costs, although these costs are not expected for this case.

3.7 ADDITIONAL RECOMMENDATIONS

Full conversion to a hydrogen-powered bus fleet will include a number of significant barriers. This report has outlined many of these challenges as well as the strategies to overcome them. However, other issues such as those pertaining to hydrogen policy must also be considered by those agencies considering a transition to hydrogen fuel. This section briefly identifies those areas in which additional consideration should be given in order to make the transition to hydrogen-fueled buses a success.

- As mentioned previously, the findings in this report are contingent on the maturation of hydrogen bus technology and careful consideration should be given to both current and expected technology costs when considering the transition to hydrogen buses.
- Although costs associated with hydrogen technology are expected to significantly drop in the coming years, it is unclear when or if those costs will reduce to a level that makes hydrogen technology competitive with diesel and other fuel technologies. As suggested by other sources, government subsidies or incentives may be necessary to make hydrogen competitive with other fuel technologies in the future. This could include government-industry collaborations on fuel production or refueling station construction. Additionally, government incentives for hydrogen bus acquisition, facility construction, or other areas could further increase the likelihood of widespread adoption of hydrogen bus technologies.
- As hydrogen technology is relatively new to most agencies, careful adherence to hydrogen regulations and standards as they apply to vehicles and facilities is essential. Various sections of the following codes are important to hydrogen infrastructure: International Fire Code; National Fire Protection Association (NFPA) 30A, Code for Motor Fuel Dispensing Facilities and Repair Garages; NFPA 52, Vehicular Fuel Systems Code; NFPA 55, Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks. Such regulations have impact all areas of the hydrogen infrastructure including production, storage, maintenance, and refueling facilities as well as some details of the hydrogen buses themselves. A detailed listing of relevant codes can be found in ETHI [30].

4. CONCLUSIONS AND DISCUSSION

While widespread public adoption of hydrogen technology fuels is a large undertaking and faces many obstacles, the transition of transit agencies such as the KAT as initial adopters can serve as an intermediate step. Whereas recent demonstration projects have focused on the introduction of hydrogen-fueled buses along specific corridors, this study considers the conversion of a full transit fleet and the requirements such a transition would place on the transit agency. This transition will require agencies to increase their transit fleet size and develop facilities for hydrogen production, storage, and refueling as well as new maintenance facilities to service the hydrogen bus fleet. This report has identified requirements for these parameters to support a fleet of hydrogen-fueled buses and has assigned some associated costs to these parameters.

The transition strategies discussed in this paper focus on KAT and consider specific characteristics of KAT operations; however, these strategies could be applied to other transit agencies with operations and characteristics. Operating budgets and financial support systems are likely to differ among transit agencies and are likely to play a major role in transit agency transition strategies. Government sponsored incentive programs and subsidies could also assist transit agencies with completing transition. Also, transition requirements could be reduced in a longer term scenario where a hydrogen support infrastructure is already present.

As hydrogen technology continues to mature, hydrogen bus performance is likely to improve. Similarly hydrogen production methods should improve, and with these improvements, some requirements identified in this paper may no longer apply or may be significantly reduced. A number of hydrogen bus demonstration projects are still underway or are currently being planned. Additional data from these projects may point to differing conclusions about support infrastructure requirements. While this study provides a guideline for transit agencies transitioning to hydrogen fuel, those agencies should consider the current state of this technology and make adjustments to these recommendations as necessary.

Still, a number of advantages and benefits have been identified for transit agencies through the transition to hydrogen fuel, particularly with expected advances in hydrogen bus technology. With the scenarios presented here, a reduction in operating expenses can be achieved. In the short-term, however, these savings are not likely as current bus costs and expenses significantly exceed those of standard transit buses.

The findings identified in this report provide an initial framework for medium sized transit agencies considering a transition to hydrogen fuels. This report also provides support for Task III of the East Tennessee Hydrogen Initiative, which will focus on developing a small scale hydrogen station at The University of Tennessee. In the event of conversion to hydrogen fuel, the support infrastructure requirements identified in this report can serve new hydrogen bus fleets and transit agency needs as well as promote hydrogen technology and help to facilitate large scale public adoption of hydrogen fuel technology for KAT as well as other medium sized transit agencies.

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APPENDIX A: METRIC CONVERSION TABLE

SI* (MODERN METRIC) CONVERSION FACTORS				
Table of APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME (Note: Volumes greater than 1000 L shall be shown in m^3)		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE	Temperature is in exact degrees	
°F	Fahrenheit	5 × (F-32) ÷ 9 or (F-32) ÷ 1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
Table of APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2000 lb)	T
		TEMPERATURE	Temperature is in exact degrees	
°C	Celsius	1.8C + 32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force & Pressure or Stress		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009)

APPENDIX B: LIST OF ACRONYMS

AC Transit	Alameda-Contra Costa Transit
B20	Biodiesel (20% Biodiesel, 80% Diesel)
CA	California
CNG	Compressed Natural Gas
CT	Connecticut
CTE	Center for Transportation and the Environment
DCFs	Decorated Carbon Fullerenes
DE	Delaware
DO	Directly Operated
ETHI	East Tennessee Hydrogen Initiative
FCB	Fuel Cell Bus
FTA	Federal Transit Administration
GIS	Geographic Information Systems
H_2	Hydrogen
HI	Hawaii
HICE	Hydrogen Internal Combustion Engine
HTDC	High Technology Development Corporation
HyDRA	Hydrogen Demand and Resource Analysis
ICE	Internal Combustion Engine
KAT	Knoxville Area Transit
Kg	Kilogram
KGIS	Knoxville (Knox County) Geographic Information System
MBRC	Miles Between Road Calls
MPFs	Metal Porhyrin Frameworks
MSA	Metropolitan Statistical Area
NAVC	Northeast Advanced Vehicle Consortium
NFPA	National Fire Protection Association
NIMBY	Not-In-My-Back-Yard
PT	Purchased Transportation
Santa Clara VTA	Santa Clara Valley Transportation Authority
SC	South Carolina
SMR	Steam Methane Reformer
TX	Texas
UAF	Urbanized Area Formula Program
ULSD	Ultra-low Sulfur Diesel
US	United States
UT	University of Tennessee
ZEBA	Zero Emissions Bay Area

APPENDIX C: SUMMARY OF KAT BUS FLEET DATA

Veh #	Type	Description	Manufacturer/ Model	Model Year	Fuel Type	Current Condition	Mileage	Age	Life	Replacement Eligibility
101	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	304,892	9	5	2006
102	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	309,713	9	5	2006
103	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	294,213	9	5	2006
104	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	306,238	9	5	2006
105	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	337,793	9	5	2006
106	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	306,752	9	5	2006
107	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	308,376	9	5	2006
108	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	297,442	9	5	2006
109	ADA	Para-Transit Van	Dodge Ram 3500/ Braun	2001	Gasoline	Poor	291,354	9	5	2006
131	ADA	Para-Transit Van	Ford E-350/ Goshen	2004	Gasoline	Good	215,739	6	5	2009
132	ADA	Para-Transit Van	Ford E-350/ Goshen	2005	Gasoline	Good	242,798	5	5	2010
133	ADA	Para-Transit Van	Ford E-350/ Goshen	2005	Gasoline	Good	152,443	5	5	2010
134	ADA	Para-Transit Van	Ford E-350/ Goshen	2005	Gasoline	Good	175,943	5	5	2010
135	ADA	Para-Transit Van	Ford E-350/ Goshen	2006	Diesel/ Biodiesel	Excellent	113,851	4	5	2011
136	ADA	Para-Transit Van	Ford E-350/ Goshen	2006	Diesel/ Biodiesel	Excellent	113,416	4	5	2011
137	ADA	Para-Transit Van	Ford E-350/ Goshen	2006	Diesel/ Biodiesel	Excellent	134,418	4	5	2011
138	ADA	Para-Transit Van	Ford E-350/ Goshen	2006	Diesel/ Biodiesel	Excellent	102,020	4	5	2011
139	ADA	Para-Transit Van	Ford E-350/ Goshen	2006	Diesel/ Biodiesel	Excellent	107,737	4	5	2011
140	ADA	Para-Transit Van	Ford E-350/ Goshen	2007	Diesel/ Biodiesel	Excellent	83,872	3	5	2012
141	ADA	Para-Transit Van	Ford E-350/ Goshen	2007	Diesel/ Biodiesel	Excellent	76,390	3	5	2012
142	ADA	Para-Transit Van	Ford E-350/ Goshen	2007	Diesel/ Biodiesel	Excellent	84,198	3	5	2012
143	ADA	Para-Transit Van	Ford E-350/ Goshen	2007	Diesel/ Biodiesel	Excellent	76,656	3	5	2012
311	Main	NSO Cutaway	Ford/Goshen	2004	Liquid Propane	Good	211,205	6	5	2010
312	Main	NSO Cutaway	Ford/Goshen	2004	Liquid Propane	Good	208,533	6	5	2010
313	Main	NSO Cutaway	Ford/Goshen	2004	Liquid Propane	Good	184,149	6	5	2010
314	Main	NSO Cutaway	Ford/Goshen	2004	Liquid Propane	Good	221,718	6	5	2010

Veh #	Type	Description	Manufacturer/ Model	Model Year	Fuel Type	Current Condition	Mileage	Age	Life	Replacement Eligibility
316	Main	NSO Cutaway	Ford/Goshen	2005	Liquid Propane	Good	153,709	5	5	2011
317	Main	NSO Cutaway	Ford/Goshen	2005	Liquid Propane	Good	172,223	5	5	2011
318	Main	NSO Cutaway	Ford/Goshen	2006	Liquid Propane	Excellent	166,053	4	5	2012
319	Main	NSO Cutaway	Ford/Goshen	2006	Gasoline	Excellent	200,003	4	5	2012
320	Main	NSO Cutaway	Ford/Goshen	2006	Gasoline	Excellent	175,843	4	5	2012
321	Main	NSO Cutaway	Ford/Goshen	2007	Liquid Propane	Excellent	113,026	3	5	2013
322	Main	NSO Cutaway	Ford/Goshen	2007	Liquid Propane	Excellent	105,890	3	5	2013
323	Main	NSO Cutaway	Ford/Goshen	2007	Liquid Propane	Excellent	101,924	3	5	2013
324	Main	NSO Cutaway	Ford/Goshen	2007	Liquid Propane	Excellent	82,129	3	5	2013
325	Main	NSO Cutaway	Ford/Goshen	2007	Liquid Propane	Excellent	104,052	3	5	2013
326	Main	NSO Cutaway	Ford/Goshen	2007	Liquid Propane	Excellent	108,024	3	5	2013
361	Main	NSO Cutaway	Ford/Goshen	2003	Liquid Propane	Good	156,206	7	5	2009
362	ADA	NSO Cutaway	Ford E-450/ Goshen	2003	Liquid Propane	Good	147,155	7	5	2009
363	Xfer Point	NSO Cutaway	Ford/Goshen	2003	Liquid Propane	Good	147,091	7	5	2010
364	ADA	NSO Cutaway	Ford E-450/ Goshen	2003	Liquid Propane	Good	125,161	7	5	2009
365	ADA	NSO Cutaway	Ford E-450/ Goshen	2003	Liquid Propane	Good	179,907	7	5	2009
366	ADA	NSO Cutaway	Ford E-450/ Goshen	2004	Liquid Propane	Excellent	142,327	6	5	2010
367	ADA	NSO Cutaway	Ford E-450/ Goshen	2004	Liquid Propane	Excellent	103,197	6	5	2010
368	ADA	NSO Cutaway	Ford E-450/ Goshen	2004	Liquid Propane	Excellent	159,529	6	5	2010
369	ADA	NSO Cutaway	Ford E-450/ Goshen	2004	Liquid Propane	Excellent	159,940	6	5	2010
370	ADA	NSO Cutaway	Ford E-450/ Goshen	2004	Liquid Propane	Excellent	216,800	6	5	2010
371	ADA	NSO Cutaway	Ford E-450/ Goshen	2004	Liquid Propane	Excellent	176,330	6	5	2010
511	Main	40 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Good	387,975	13	12	2009
512	Main	40 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Good	339,516	13	12	2009
513	Main	40 foot RTS	Nova/RTS	1999	Diesel/ Biodiesel	Fair	310,603	11	12	2011
514	Main	40 foot RTS	Nova/RTS	1999	Diesel/ Biodiesel	Poor	288,893	11	12	2011
515	Main	40 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	49,044	1	12	2021
516	Main	40 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	43,626	1	12	2021
517	Main	40 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	39,013	1	12	2021
518	Main	40 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	43,779	1	12	2021
519	Main	40 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	44,861	1	12	2021

Veh #	Type	Description	Manufacturer/ Model	Model Year	Fuel Type	Current Condition	Mileage	Age	Life	Replacement Eligibility
520	Main	40 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	35,605	1	12	2021
652	Main	40 foot Lowfloor	Nova	1999	Diesel/ Biodiesel	Poor	263,562	11	12	2011
653	Main	40 foot Lowfloor	Nova	1999	Diesel/ Biodiesel	Poor	213,427	11	12	2011
654	Main	40 foot Lowfloor	Nova	1999	Diesel/ Biodiesel	Poor	219,218	11	12	2011
655	Main	40 foot Lowfloor	Nova	1999	Diesel/ Biodiesel	Poor	227,704	11	12	2011
656	Main	40 foot Lowfloor	Nova	1999	Diesel/ Biodiesel	Poor	197,915	11	12	2011
657	Main	40 foot Lowfloor	Nova	1999	Diesel/ Biodiesel	Poor	205,087	11	12	2011
701	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	281,397	8	10	2012
702	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	304,308	8	10	2012
703	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	267,778	8	10	2012
704	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	255,076	8	10	2012
705	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	333,163	8	10	2012
706	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	228,948	8	10	2012
707	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	221,021	8	10	2012
708	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	248,391	8	10	2012
709	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	272,753	8	10	2012
710	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	251,958	8	10	2012
711	Main	30 foot Opus	Optima Bus Corp	2002	Diesel/ Biodiesel	Good	203,438	8	10	2012
712	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	197,399	7	10	2013
713	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	187,874	7	10	2014
714	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	219,541	7	10	2013
715	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	140,572	7	10	2013
716	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	184,311	7	10	2013
717	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	259,585	7	10	2013
718	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	198,692	7	10	2013
719	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	231,229	7	10	2013
720	Main	30 foot Opus	Optima Bus Corp	2003	Diesel/ Biodiesel	Good	134,979	7	10	2014
901	Main	35 foot RTS	Nova/RTS	1996	Diesel/ Biodiesel	Fair	491,820	14	12	2008
903	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	439,746	13	12	2009
904	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	612,871	13	12	2009
905	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	571,422	13	12	2009
906	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	565,378	13	12	2009
908	Main	35 foot RTS	Nova/RTS	1997	Diesel/	Fair	540,337	13	12	2009

Veh #	Type	Description	Manufacturer/ Model	Model Year	Fuel Type	Current Condition	Mileage	Age	Life	Replacement Eligibility
					Biodiesel					
909	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	654,634	13	12	2009
910	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	641,589	13	12	2009
912	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	558,363	13	12	2009
913	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	542,410	13	12	2009
914	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	593,197	13	12	2009
916	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	486,077	13	12	2009
919	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	527,902	13	12	2009
920	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	507,178	13	12	2009
921	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	548,286	13	12	2009
922	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	513,132	13	12	2009
923	Main	35 foot RTS	Nova/RTS	1997	Diesel/ Biodiesel	Fair	513,031	13	12	2009
931	Main	35 foot Chance	Optima Bus Corp	2004	Diesel/ Biodiesel	Excellent	132,443	6	10	2014
932	Main	35 foot Chance	Optima Bus Corp	2004	Diesel/ Biodiesel	Excellent	172,991	6	10	2014
933	Main	35 foot Chance	Optima Bus Corp	2004	Diesel/ Biodiesel	Excellent	147,503	6	10	2014
934	Main	35 foot Chance	Optima Bus Corp	2004	Diesel/ Biodiesel	Excellent	180,883	6	10	2014
935	Main	35 foot Chance	Optima Bus Corp	2005	Diesel/ Biodiesel	Excellent	149,439	5	10	2015
936	Main	35 foot Chance	Optima Bus Corp	2005	Diesel/ Biodiesel	Excellent	167,871	5	10	2015
937	Main	35 foot Chance	Optima Bus Corp	2005	Diesel/ Biodiesel	Excellent	169,770	5	10	2015
940	Main	35 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	33,243	1	12	2021
941	Main	35 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	48,991	1	12	2021
942	Main	35 foot Lowfloor	GILLIG	2009	Diesel/ Biodiesel	Excellent	39,963	1	12	2021
9672	Main	40 foot RTS	Nova/RTS (Leased)	1996	Diesel/ Biodiesel	Fair	461,368	14	12	2008
T-22	Main	Trolley	DUPONT	1999	Diesel/ Biodiesel	Poor	252,647	11	10	2009
T-23	Main	Trolley	DUPONT	1999	Diesel/ Biodiesel	Poor	266,999	11	10	2009
T-24	Main	Trolley	DUPONT	1999	Diesel/ Biodiesel	Poor	264,996	11	10	2009
T-25	Main	Trolley	DUPONT	1999	Diesel/ Biodiesel	Poor	247,879	11	10	2009
T-26	Main	Trolley	DUPONT	2000	Diesel/ Biodiesel	Poor	195,561	10	10	2010
T-28	Main	Trolley	DUPONT	2001	Diesel/ Biodiesel	Poor	144,379	9	10	2011
T-29	Main	Trolley	DUPONT	2002	Diesel/ Biodiesel	Poor	113,304	8	10	2012
T-31	Main	Trolley	Gillig	2008	Diesel/ Biodiesel	Excellent	35,083	2	12	2020
T-32	Main	Trolley	Gillig	2008	Diesel/ Biodiesel	Excellent	32,295	2	12	2020
T-33	Main	Trolley	Gillig	2008	Diesel/	Excellent	25,603	2	12	2020

Veh #	Type	Description	Manufacturer/ Model	Model Year	Fuel Type	Current Condition	Mileage	Age	Life	Replacement Eligibility
					Biodiesel					
T-34	Main	Trolley	Gillig	2008	Diesel/ Biodiesel	Excellent	25,562	2	12	2020

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Report No. FTA-TN-26-7033-2011.2