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INTERIOR AND EXTERIOR NOISE EMITTED BY A FUEL CELL TRANSIT BUS

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1. INTRODUCTION

Fuel cell engines are being developed for use in the automotive industry. The increasing interest in fuel cell powered vehicles is attributed to many potential advantages offered, such as increased efficiency, decreased emissions, and lower maintenance. In addition to these potential benefits to society, other benefits have been mentioned concerning fuel cell vehicles. Among these are decreased vibration and lower sound pressure levels (SPLs). Technical and popular literature has cited fuel cell vehicles as being less noisy than conventional gasoline- and diesel-powered vehicles [1, 2]. Quieter vehicles are desired because of the fact that driving in excessive noise levels can cause driver fatigue and lack of concentration [3]. Among motorists, drivers of commercial vehicles are particularly vulnerable to the effects of driving noise, due to the long periods that are spent driving. In addition, high levels of noise in vehicles can mask warning signals from the vehicle being driven and from other motorists. Therefore, in the interest of health and safety for the general population, it is important for vehicle manufacturers to make efforts to reduce the level of noise in vehicles, particularly in commercial vehicles [3].

Currently, most manufacturers use qualitative statements to characterize the level of noise emitted from vehicles. Words such as “quiet” generally fail to provide a good understanding of the level of noise emitted, especially when comparing vehicles [3]. While fuel cell vehicles are reported to be “quiet”, little quantitative information regarding the noise emitted from these vehicles has been documented and published. The purpose of these tests was to quantify sound pressure levels emitted from a fuel cell powered transit bus operating at stationary conditions. The data is vital to the noise control community in determining the realized benefit of operating fuel cell vehicles. While stationary, the bus was tested to obtain representative noise levels both inside and outside the bus. Vehicle components, such as the air conditioning system and air compressor, that are practically inaudible when used in gasoline or diesel vehicles become noticeable when used in a fuel cell powered vehicle. Sound pressure levels emitted from the fuel cell bus were quantified with various equipment configurations to determine the influence of these auxiliary components. The overall test results from the fuel cell bus were also compared to test results from similar sized busses that use conventional diesel power plants. In addition to stationary tests, interior acoustic levels were monitored while driving to determine the degree to which normal operation affects the noise levels emitted. Since city busses typically operate at low speeds, the effect of tire noise on exterior noise levels is not investigated in this paper. While

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this study only provides information concerning noise levels specific to the unique bus tested, application can be made to similarly equipped fuel cell vehicles. Findings from this study provide designers with achieved sound levels in fuel cell vehicles and with information about specific equipment or components that need to be acoustically modified.

2. BACKGROUND

The testing was performed using a 30-ft (9·1 m) liquid fuel phosphoric acid fuel cell (PAFC) transit bus at the University of Florida Fuel Cell Research and Training Laboratory. The bus employs a hybrid arrangement of a 50 kW PAFC engine in parallel with nickel–cadmium batteries on a Bus Manufacturing Incorporated (BMI) chassis. This bus was the first of three proof-of-concept vehicles (also known as test bed bus 1 or TBB-1) built with funding from the U.S. Department of Energy, U.S. Department of Transportation, and the South Coast Air Quality Management District, and was developed by H-power and Georgetown University with the University of Florida as a sub-contractor [4]. Demonstrations of the fuel cell technology in the bus are performed throughout the state of Florida with funding provided by the State of Florida Department of Community Affairs Energy Office.

3. EQUIPMENT AND TESTING CONFIGURATION

The PAFC bus was tested to quantify its acoustic emission. A testing method similar to the one used by Björkman [5] was employed, with the notable exception that the busses in this testing were stationary. Specifically, the bus was located on a flat concrete and asphalt surface away from buildings or other objects that would reflect an appreciable amount of noise. Data were collected on four separate days with various parking orientations of the bus. Different orientations were used to ensure that unknown environmental variables, due to configuration and location, did not cause bias error at any of the measurement points. To measure the sound pressure levels, a Brüel and Kjær condenser microphone head (Model 4190) and preamplifier (Model 2669) were used. In order to reduce any wind noise, a windscreen was attached to the head of the microphone. Using a Brüel and Kjær Nexus sound analyzer, the microphone signal was “*A*” weighted. Use of this equipment in prescribed arrangement is the same as using a standard sound level meter. The “*A*” weighting, used in similar studies [6–8], is also the weighting scale used by OSHA to establish acceptable work place sound levels [3]. In addition, data were collected from three diesel busses currently in service at the City of Gainesville Regional Transit System. Maximum SPLs were recorded at idle operating conditions for these busses.

Six points around the perimeter of the fuel cell bus were selected as observation points for measuring the SPLs as shown in Figure 1. These points were located at the front center, front door curbside, back door curbside, back center, and across from both doors on the driver’s side of the bus. All measurements outside of the bus were taken at a distance of 2·75 m from the respective side of the bus (elevation 1·5 ± 0·2 m above ground). A distance of 2·75 m was chosen to prevent background noise from dominating the low sound pressure levels emitted by the bus. Also shown in Figure 1, six points inside the bus were selected as observation points for measuring interior noise levels. These points included the driver’s seat and passenger’s seats near the front and middle of each side of the bus. Measurements at the center of the back wall of the bus’s interior were also taken. The measurements inside the bus were taken at these points at passenger seated head level (1·5 ± 0·2 m above floor).

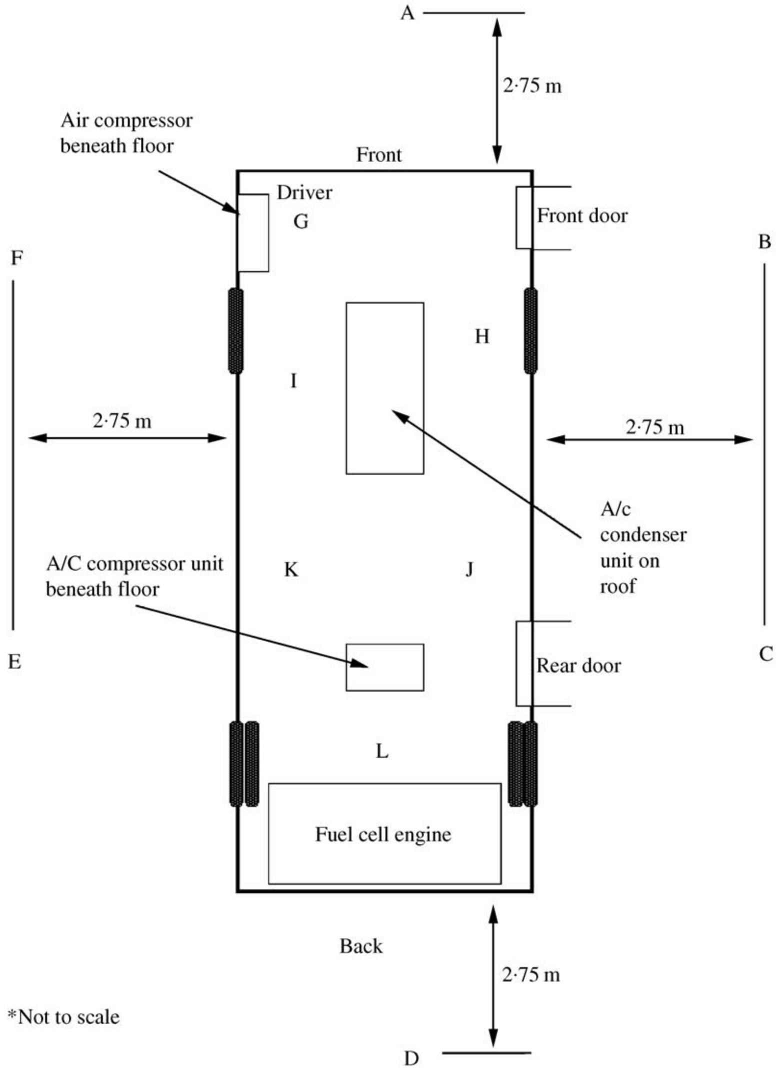

Figure 1. Measurement positions for interior and exterior of the fuel cell bus.

Head level was employed as the measurement position in addition to the "*A*" weighting to achieve responses comparable to that of human ear response.

4. EXPERIMENTAL PROCEDURE

Background SPLs were measured while the bus was not operating. According to the normal operating procedure for this bus, the bus was started to establish normal operating conditions [4]. No acoustic measurements were made during the start-up period (30–45 min). The temperature on the testing days ranged from 35 to 38°C. After normal operating conditions were achieved and output power parameters were established, the bus was parked in the desired orientation and acoustic measurements were made using the measurement points and distances mentioned above. Figure 1 shows the location at which each set of data was collected. The acoustic measurements were taken using a horizontal in-plane sweeping motion in order to find the maximum acoustic level within a 0·5-m range. The maximum value observed was recorded. The sweep was performed to reduce localized effects caused by the variation in the directivity of the radiated acoustic field. After the measurements were taken, the bus was shut down. No acoustic measurements were taken during the shutdown period. This measurement procedure was repeated four separate times to provide the basis for statistical verification of results. A single set of data was collected using a similar procedure for the city busses used for comparison.

5. RESULTS AND DISCUSSION

Measurements of the sound pressure levels outside the fuel cell bus were taken for various equipment configurations. Four sets of data were taken for each configuration and location. These values were averaged and an uncertainty analysis was performed to determine the possible error in the results. The average background SPL was 51 dB(A) (re. 20 μPa). Table 1 shows the results for average sound pressure levels outside of the bus and the associated uncertainty. A 90% confidence level for uncertainty was calculated using the Student's *t*-distribution [9]. Values of the average maximum sound pressure level and uncertainty for each inside location are shown in Table 2. The letters referring to the location at which measurements were taken refer to the locations presented in Figure 1. The configuration refers to the equipment operating during each measurement, as

TABLE 1

Results of exterior sound pressure level testing

Location	Configuration	Maximum SPL (dB(A))	Uncertainty 90% (dB(A))
A	I	66	± 3·4
	II	67	± 2·2
	III	73	± 0·9
	IV	73	± 1·3
B	I	66	± 1·8
	II	67	± 1·9
	III	70	± 1·0
	IV	69	± 2·7
C	I	67	± 1·5
	II	70	± 1·5
	III	71	± 2·2
	IV	69	± 1·9
D	I	69	± 1·3
	II	70	± 1·1
	III	70	± 1·5
	IV	70	± 1·5
E	I	68	± 1·7
	II	69	± 0·7
	III	71	± 1·7
	IV	69	± 1·7
F	I	67	± 3·5
	II	68	± 1·9
	III	70	± 1·6
	IV	71	± 2·9

TABLE 2

Results of interior sound pressure level testing

Location	Configuration	Maximum SPL (dB(A))	Uncertainty 90% (dB(A))
G	I	62	± 2·4
	II	70	± 0·4
	III	71	± 0·4
	IV	65	± 1·9
H	I	61	± 3·4
	II	72	± 2·3
	III	72	± 0·1
	IV	65	± 1·0
I	I	60	± 4·0
	II	71	± 0·3
	III	72	± 0·6
	IV	64	± 2·1
J	I	60	± 1·9
	II	71	± 1·1
	III	72	± 0·6
	IV	64	± 2·9
K	I	60	± 2·1
	II	71	± 0·5
	III	72	± 0·3
	IV	63	± 1·7
L	I	61	± 3·2
	II	69	± 0·4
	III	69	± 0·5
	IV	64	± 3·0

follows. Configuration I: fuel cell engine; configuration II: fuel cell engine, air conditioner; configuration III: fuel cell engine, air conditioner, air compressor; configuration IV: fuel cell engine, air compressor.

The results in Table 1 show that the sound levels outside the bus in position A (closest to the air compressor) were primarily dominated by the sound produced by the air compressor, which, when running, caused an average increase of 7 dB(A) over the SPL produced by the fuel cell engine alone. The interior SPLs (Table 2) at all positions are most affected by the air conditioner, which, when running produces an average increase of 11·7 dB(A) over the sound level produced by the motor and fuel cell alone. Even though the sound levels are relatively low when the air conditioner and air compressor are operating, it is desirable to further reduce the noise from these sources. Because the fuel cell engine emits low SPLs, noise from the air conditioning unit and other components becomes more noticeable. Therefore, new design problems are presented to designers of fuel cell vehicles to acoustically insulate or control these previously masked sounds. While fuel cells may offer an overall noise reduction in transportation, redesigning or controlling existing equipment to reduce the noise production brings new challenges to the noise control industry.

Similarly during driving, other sounds, which may not have been noticeable on vehicles using louder engines, can be heard. During a driving cycle (at speeds of less than 35 mph), conventionally masked sounds emitted from air suspension release, power steering, and the braking system were observed. However, these SPLs were not outside of the experimental uncertainty for the stationary measurements. Overall, interior sound levels during driving were determined to be similar to the values obtained from the stationary tests. It is also important to note that sound levels were independent of power output from the fuel cell engine and speed of the drive system. This phenomenon can be attributed mainly to the fact that the fuel cell bus's drive train is driven by an electric motor as opposed to a mechanical transmission and internal combustion engine, which produce more noise as the rotational speed of the engine increases.

It is important to note that the data is only applicable to this specific fuel cell engine that is operated near ambient pressure and does not require a compressor/expander. The compressor/expander on early proton exchange membrane fuel cell (PEMFC) systems and other pressurized systems has been noted to produce high acoustic emission [10].

For comparison purposes, maximum SPL data were collected from three diesel busses currently in service. The highest sound pressure level for the fuel cell bus at 2·75 m occurred at the front center (location A) with all auxiliary equipment operating (configuration III). This maximum SPL at a distance of 2·75 m was measured to be 73 dB(A). As shown in Table 3, all of the diesel-powered busses were significantly louder than the fuel cell vehicle tested.

6. CONCLUSIONS

The following conclusions can be derived from these tests. First, the PAFC bus studied is significantly quieter than conventional diesel busses. Since PAFC engines do not produce as much noise as diesel engines, sounds from vehicle components such as the air conditioner, suspension, brakes, and compressors are unmasked in PAFC vehicles. In order to avoid potential aggravation of drivers and passengers of fuel cell vehicles, unmasked noise sources should be redesigned in order to reduce the amount of noise heard by occupants of the vehicle. Also, it is important to note that the results of this study are specific to the bus tested. This bus was powered by a PAFC engine, which operates near ambient pressure and therefore requires no compressor/expander in the fuel cell engine. Fuel cell engines containing pressurized stacks, such as the PEMFC engine, require the use of an air compressor to pressurize the flow into the stack and an expander to reduce the losses caused by compression. The use of such equipment may drastically alter the SPLs emitted. In the case of the bus tested, the air conditioner caused the greatest noise increase inside the bus, while the compressor (used for air brakes and other auxiliary equipment) caused the greatest noise increase outside, near the front of the bus. The noise produced by these two components should be given consideration when designing future fuel cell bus models. Finally, fuel cell vehicles offer a new hope for noise reduction of the power source in transportation, but also pose many new challenges for the noise control industry in the form of redesign or modification of existing equipment before the fuel cell vehicle can be considered a feasible noise control measure.

TABLE 3

Sound pressure levels for various busses

Vehicle	Maximum SPL at 2·5 m (dB(A))
Gillig 50′ bus (1995)	84
Orion 30′ bus (1989)	82
GMC 35′ bus (1983)	87
PAFC fuel cell bus	73

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