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DESIGN, FABRICATION AND ANALYSIS OF AN AUXILIARY POWER UNIT ON A HEAVY-DUTY TRUCK TO POWER THE HVAC SYSTEMS OF THE TRUCK DURING DRIVER OFF-DUTY CONDITIONS

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DESIGN, FABRICATION AND ANALYSIS OF AN AUXILIARY POWER UNIT ON A HEAVY-DUTY TRUCK TO POWER THE HVAC SYSTEMS OF THE TRUCK DURING DRIVER OFF-DUTY CONDITIONS

By

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A REPORT

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LIST OF ABBREVIATIONS

EPA – The Environmental Protection Agency

DOT – Department of Transportation

APU – Auxiliary Power Unit

CO_2 – Carbon-di-oxide

ULSD – Ultra low sulfur diesel

HVAC – Heating, Ventilation and Conditioning

CAT – Caterpillar

BSFC – Brake specific fuel consumption

SOC – State of charge

NVH – Noise, Vibration and Harmonics

APS – Advanced Power Systems

2-D – 2 Dimensional

Amp – Amperes

rpm – Revolutions per minute

db – decibels

OSHA - Occupational Safety and Health Administration

HMW – Humvee

℃ – Degrees Celsius

mins – Minutes

CFM – Cubic feet per minute

mm - Millimeters

L x W x H – Length x Width x Height

AN fittings – Army Navy fittings

AC – Alternating current

GFCI – Ground fault circuit interceptor

BTDC – Before top dead center

A/C – Air-conditioner

ABSTRACT

Currently, one of the biggest challenges the world is facing is energy insufficiency. One of the contributors to energy consumption in United States are the idling semi-trailer trucks. In May 2001, President Bush issued The National Energy Policy in which he directed The Environmental Protection Agency (EPA) and Department of Transportation (DOT) to reduce the idling of trucks. This was done in order to reduce energy consumption by lowering fuel consumption and emissions coming out of semi-trailer trucks in the United States of America.

This project deals with the efforts of installing an Auxiliary Power Unit (APU) as a device to reduce the idling on a Freightliner Argosy Auto Transport. A Yanmar YDG3700 series diesel generator set was mounted on the truck as an APU in order to reduce the fuel consumption and emissions of the truck. It was also used to power the 12V/120V accessories inside the truck's cabin, charge the truck's batteries and power the truck's block heater. In order to make the APU operation silent, a new exhaust system was designed and fabricated and mufflers were installed in it. Various engineering reviews were conducted and decisions were made to install the entire system on the truck.

In order to validate the results, various thermal and noise tests were conducted on this system. A load test was conducted to observe the load bearing capacity of the APU. Based on its results, calculations were done to estimate the efficiency of the APU operation. Tests were conducted to observe the temperatures reached inside the systems and appropriate ventilation requirements were selected for safe operation of the system. Sound measurement tests were conducted to validate if the APU was actually an aid to the driver during rest times. The sound measurements were made in a real time simulated truck rest stop environment. Apart from the tests, parallels were drawn between the truck's idling engine and the APU for fuel consumption and CO_2 emissions and conclusions were made on the saving in fuel consumption and emissions.

1. INTRODUCTION

Every human being needs sleep for his/her body to function properly. Same is the case with heavy-duty truck drivers. Usually, truck drivers have job requirements, which require them to drive thousands of miles in order to deliver their assigned consignments. They cannot cover the entire distance in a day and require rest stops in between. This is termed as off-duty condition. During their off-duty condition, depending on the weather, the driver may need air conditioning or heating inside the truck's cabin. In order to achieve this, often drivers keep the truck's diesel engine on idling so that the truck's air conditioner or heater can be operated so as to achieve the suitable temperature conditions inside the cabin. The truck drivers also keep the engine on idling in order to keep the truck's batteries charged for operation of in-cabin accessories like lights, microwave, refrigerator, etc. and to keep the engine warm to ensure cold starts. However, this leads to increased fuel consumption, emission and noise pollution.

As per the exhaust emission standards managed by the Environmental Protection Agency (EPA), heavy duty vehicles should restrict their exhaust emissions below 15ppm sulfur emissions [1] and use ultra-low sulfur diesel (ULSD) fuel only. Also, EPA has proposed regulations to reduce greenhouse gas emissions from heavy-duty engines and vehicles (Class 8 trucks). These new regulations will require their fuel economy to rise by 40% [2] by the year 2027, as compared to 2010 statistics. Thus, running the engine on idling with the air-conditioner or heater running is a bad idea for drivers, as it will lead to increased fuel consumption.

With the above restrictions and regulations being proposed, there was a need to look at other technologies to reduce the idling time on trucks. However, it was also important to provide equivalent heating/cooling in the cabin as obtained from truck's main HVAC system. Some major idling reduction technologies are as follows [3]:

- Cab or Bunk Heaters
- Coolant Heaters
- Energy Recovery System
- Storage Air Conditioners
- Automatic Engine Stop-Start Controls
- Auxiliary Power Units

Out of all the above mentioned technologies, the Auxiliary Power Unit (APU) is the most economical option as it provides the driver access to all the equipment in the truck's cabin, like heating, cooling, 12V sockets, television, etc. The other options do not provide the same advantages as the APU and also dictate the stopping locations in order to use them. For example, storage air conditioners require a location with power outlets for their operation. Not all truck stops will be equipped with power outlets, making this technology disadvantageous.

APUs are basically small and compact devices on a vehicle that generate energy for functions other than driving the vehicle. In other words, APUs are used to provide energy to charge the vehicle’s batteries during engine shutdown time, power the electrical components of the vehicle when the vehicle’s engine is shut off and so on. An APU generally consists of a small capacity gasoline or diesel operated engine or a fuel cell, which drives a generator in order to produce electricity for powering the electric equipment inside the vehicle and for charging the vehicle’s batteries. The exhaust from the APU can be used to heat the fuel system so that the truck’s main engine can be started easily. By using these devices, the driver can use portable heaters/coolers powered by the electricity generated by the APU during off-duty conditions and thereby adhere to the idling restrictions set by the DOE and EPA.

This project was done on a 2001 Freightliner Argosy semi-truck, as an effort to reduce the idling and emissions from its six-cylinder CAT engine. Figure 1 shows the image of the Argosy truck used for this project.

Figure 1: 2001 Freightliner Argosy truck on which the APU was to be mounted

The specifications of the truck are given in Table 1 below [4] [5] [6].

Dimensions (in m) (approx.)	
Overall Length	12.2
Overall Width	2.3
Overall Height	4.2
Wheel Base	4.3
Mass (in KG)	
Gross Vehicle Mass (in KG)	28115
Gross Combination Mass (in KG)	60000
Engine	
Make	Caterpillar 3406
Model	Diesel – 6 – in-line
Capacity (cc)	14640
Minimum Power (bhp)	375
Maximum Power (bhp)	465
Rated Speed (rpm)	1800-2100
BSFC @ 1800 rpm (g/kW-hr)	208.1
Compression Ratio	14.5:1

Table 1: Technical specifications for 2001 Freightliner Argosy truck with CAT3406 engine

A Yanmar YDG 3700 series generator set was used as an APU. This generator set had a L70V model diesel single cylinder engine. Figure 2 shows the image of the generator set.

Figure 2: Yanmar YDG3700 series generator set used as an APU for this project

The technical specifications for the generator set are given in Table 2 below.

Dimensions (L x W x H) (inches)	25.6 x 19.5 x 20.9
Dry Weight (in KG)	82.1
AC Output	
Max. (kW)	3.7
Rated (kW)	3.5
DC Output V-A (W)	12V – 8.3A (100)
Rotation Speed (rpm)	3600
Engine	
Make/Model	Yanmar L70V6-GY
Type	1 Cyl. Direct Injected, Air Cooled Diesel
Starting System	Electric Start with Recoil
Fuel Capacity (liters)	12.96
Noise at Continuous Rated Output (Average in 4 Directions)	
At 1 M distance (dbA)	93
At 7 M distance (dbA)	82

Table 2: Technical Specifications of Yanmar YDG3700 series generator which is the APU in this project

As per the data collected from the Operations Manager of the Argosy, it idles for approximately 126 hours in a year. From the report by Han Lim, a 2001 Argosy consumes 0.82 gallons of diesel per hour while idling [26]. On extrapolating for 126 hours, the truck consumes 103.2 gallons in a year only during idling. Also, the battery SOC of the Argosy being used in this project, degrades very fast, and this called for frequent charging when the truck was not mobile. Furthermore, the block heaters installed in the Argosy needed electrical power to function when the truck's engine is turned off. Due to all these reasons, it was advantageous to mount an APU on this truck.

Various engineering decisions were taken in order to install the APU on the Argosy. In order to mount the APU on the truck, various parameters such as cost, accessibility, load capability and space constraints were considered. During the APU operation, it was expected that the temperatures inside the mounting box would be high. Thus, ventilation options were devised and a solution was decided upon weighing factors such as cost, ease of use and level of ventilation achieved. To achieve silent operation of the APU, it was important to have a good exhaust system and dampen the vibrations produced in the system. Engineering design reviews were conducted and an exhaust system was designed in order to achieve a considerable sound transmission loss. A very important feature of this system was to power the electrical equipment inside the truck's cabin. Proper electrical wiring circuits were designed and implemented in order to power the electrical equipment inside the truck, charge the truck's batteries and run the auxiliary heaters. This project highlights all the above steps taken to install an APU on the Argosy.

1.1. Functional requirements

Following five functional requirements were set for this project:

1. **Ease of Use – (generator set, fuel system, controls)**
   The Yanmar YDG3700 generator set should be easy to start from the truck's cabin, the fuel system should be designed and fabricated in such a way that the APU should start immediately upon cranking, the controls to operate the electricals should be ergonomically placed and easy to use.

2. **NVH and exhaust odor should be no worse than the production engine's noise level**
   The operation of the APU is mostly going to happen during the night when the driver takes rest in a rest stop. Hence, the noise generated by the APU should be minimum.

3. **Truck's operation should not be affected**
   All the connections to and from the APU should be such that the truck's original operation should not be compromised. Even when the APU is not in use, all the features of the truck should be operable.

4. **Generator set should be able to operate HVAC in truck's cabin, charge trucks batteries and run the block heaters**
   The Argosy has 4 batteries in parallel configuration. There is a 120V Genius battery charger installed on the truck to charge these batteries. One of APU's main tasks is to charge the truck's batteries using this charger in order to maintain the SOC of the batteries. The APU should also provide power to operate portable heater/cooler inside the truck's cabin to satisfy the HVAC requirements of the driver.

5. **System should be safe to use**
   The system should be safe to use and should not cause any danger to the driver operating the system or to the truck on which it is mounted.

1.2. Testing

In order to confirm if the above mentioned functional requirements were fulfilled, the following validation tests were conducted:

1. **To measure the maximum fuel level required for APU to function**
   The fuel level test was conducted before making decisions on the fuel system design to measure the maximum depth from the APU engine's fuel pump that the fuel level can be at, so that the fuel pump can draw the fuel into the system.

2. **To calculate the efficiency of APU operation**
   Load test was conducted where the APU was loaded with different electrical loads and the output from it was observed. Based on the results, calculations were done for efficiency. This was compared to idling truck engine.

3. **To measure the sound emitted from the system**
   A simulated truck rest stop environment was created and sound measurements were made at certain strategic points. These measurements were made for different load conditions. Comparisons were drawn with truck's engine when it's idling.

4. **To measure the temperatures attained in the system**
   Temperature measurements were made inside the APU mounting box and at the exhaust of the APU. The former was done to validate the ventilation arrangements and the latter was done for exhaust muffler study.

5. **To extrapolate the fuel consumption and emissions results to Argosy's values**
   Fuel consumption of the APU was measured and its CO_2 emissions were calculated. Similar measurements were made for the Argosy. Both the readings were compared and inferences were drawn on the savings in fuel consumption and emissions.

2. <u>DESIGN AND FABRICATION</u>

Based on the proposed functional requirements stated in Section 1.1, this chapter explains the various engineering decisions taken during design and fabrication of the components of the APU system. A detailed design review was conducted before finalizing the proposed solutions to each problem. The reviews were performed considering various parameters like cost, ease of fabrication and maintenance, user-friendliness and so on.

2.1. Mounting APU on the truck

The Yanmar YDG3700 series generator set (i.e. the APU used in this project) comprised of a single cylinder diesel engine, a muffler, an alternator and a control panel. All these components came assembled in a metal frame. In order to dampen the vibrations caused by the engine, rubber dampers were provided between the engine and the frame. With this packaging of the APU, decisions were to be made on mounting it on the truck.

In order to mount the APU on the truck, following requirements were taken under consideration:

i. Easy accessibility of APU
ii. Low cost to build an enclosure in available space
iii. Qualifying to dimensions of the APU
iv. Ventilation requirements of APU
v. Access to other equipment of the truck
vi. Environmental Protection

2.1.1. Selecting a location to mount the APU

After primary visual check, it was observed that the best location for mounting the APU was in the place of the truck's toolbox. Figure 3 shows the location of the toolbox on the truck.

Figure 3: Location of the toolbox on the truck for mounting the APU

Dimensions of the toolbox and APU were taken. It was seen that the width of the APU with its stock muffler was 2” more than the width of the toolbox. However, without the muffler, there was a large clearance between APU and toolbox walls. After considering factors such as easy accessibility of toolbox, cost and ease of machining on the toolbox, it was decided to remove the stock muffler instead of finding a new location for the APU. Dimensions of the APU without its supporting rod frame and muffler and truck’s toolbox are shown in Table 3.

Sr. No.	Dimensions	APU (in.)	Truck’s Toolbox (in.)
1.	Width	21.5	36
2.	Depth	14.5	16
3.	Height	17.25	17.5

Table 3: Comparison of dimensions of generator set and toolbox

From Table 1, it was concluded that the APU could be installed in the toolbox of the truck itself. To visualize and check the fitment of the APU inside the toolbox, a computer aided design was made using Pro-Engineer Creo software, as shown in Figure 4.

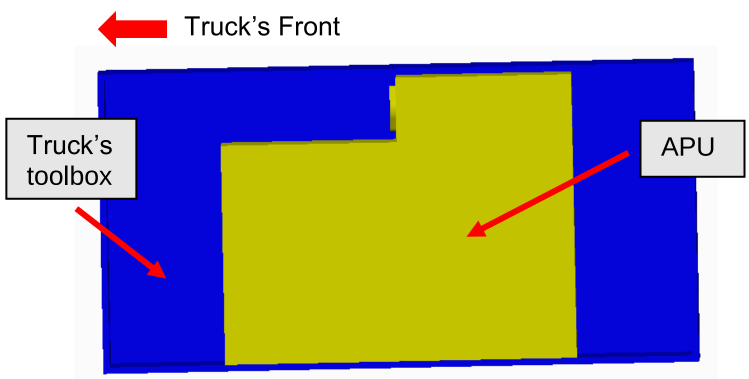


Figure 4: Front view of computer aided drawing of APU inside the toolbox

From Figure 4, it is evident that length and width of the APU, including tolerances, were within the boundary limits of the toolbox. Clearance for the height of the APU was the only issue that had to be considered while mounting the generator set into the toolbox. After considering all the above results, the truck’s toolbox was chosen as the location to mount the APU.

2.1.2. Mounting of APU in the toolbox

The toolbox had a key-lock system that opened the door of the toolbox. The key was never supplied when Michigan Tech APS Labs purchased the truck and hence, the toolbox’s key-lock system had to be broken in order to open the toolbox. The toolbox was cleaned and the holes left in it due to breaking of the previous key-lock system were mended. A new lock system was installed on the toolbox. This system prevented the need for keys and hence eliminated the problem of lost keys in the future. Figure 5 shows the modified look of the toolbox mounted on the Argosy truck.

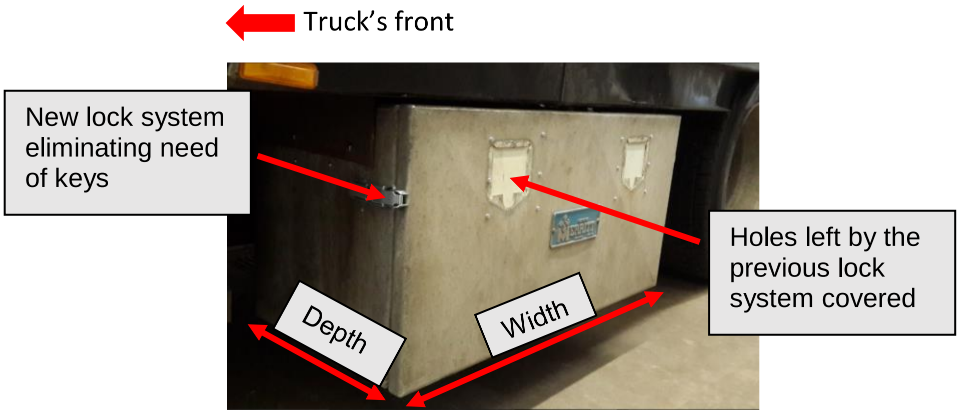


Figure 5: Modified and mended toolbox mounted on Argosy truck

As discussed in the previous section, the height of the generator set was an issue as there was very little clearance space between the cylinder head of the APU engine and the top surface of the toolbox. To prevent any contact between the engine's cylinder head and surface of the toolbox, a hole was drilled in the surface of the toolbox right above the cylinder head. This helped to solve the clearance height problem between the APU and toolbox. It was predicted that this hole in the toolbox could help in ventilation. The hole could act as a path for the heat from the engine to exit the toolbox.

A generator set is sold universally on a metal frame. Rubber dampers are used between the generator's engine base and the frame to reduce vibrations. Those same rubber dampers were mounted between the APU and toolbox to reduce vibrations. Figure 6 shows the APU mounted inside the toolbox.

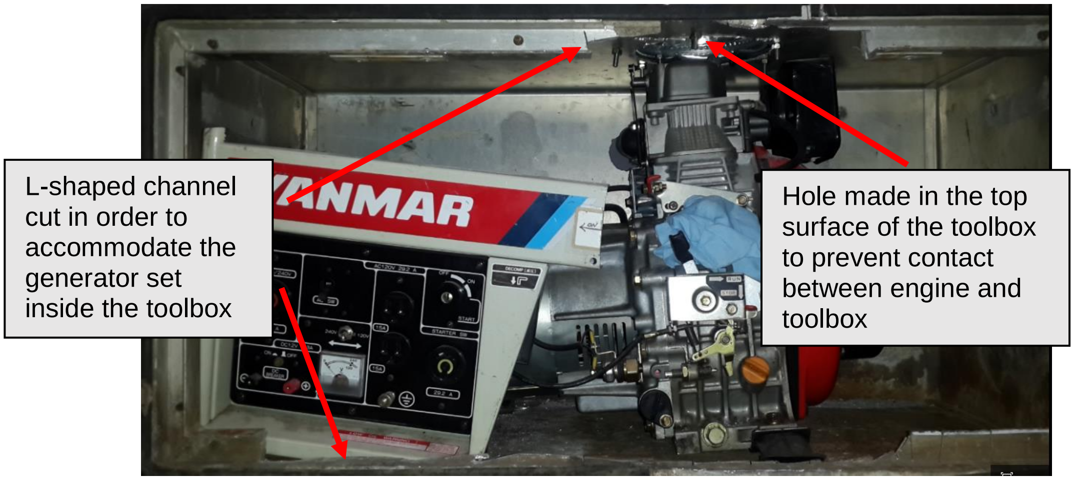


Figure 6: Modifications done to the toolbox for APU installation

2.2. Ventilation in APU mounting case

This project required the APU to be mounted in an enclosure so as to protect it from dirt and debris from the road, during journeys. The 320cc APU engine used in this project will produce a large amount of heat over large operation times. To prevent the problems, cause by heat enclosed in the toolbox, it was necessary to provide proper ventilation.

2.2.1. Natural vs Forced Convection

Since the engine is air-cooled, either natural air convection or forced convection are the processes that can be used as means to ventilate the toolbox.

- **Natural Air Convection:** This is a phenomenon where air flows due to the density difference of air in a medium, due to a temperature gradient. During the phenomenon of natural air convection, air surrounding a heat source draws heat from the source, becomes less dense and rises. The surrounding, cooler air then travels to replace it. This cooler air is then heated after coming in contact with heat source and the process continues, forming a loop. This loop is also called convection current.

  In our case, this process transfers heat energy from the bottom of the toolbox to the top of the toolbox. The driving force for natural convection is buoyancy, due to differences in air density.

- **Forced Air Convection:** This is a phenomenon where air flows in a medium due to means of an external source, like a fan, blower, etc. Forced air convection is generally used if the heat generated by the heat source is very high and natural convection won't be sufficient enough to ventilate the space.

2.2.2. Solutions available for ventilation

The Yanmar service manual states that the maximum operating temperature for the APU should not be more than 80℃. Temperatures higher than the limit can result in effects like melting of electrical wire insulation, breakdown of the engine oil and so on.

The air-cooled APU engine has a flywheel fan. Along with the fan, to achieve enhanced cooling, a hole was drilled in the bottom surface of the toolbox. It was covered by a slotted metal plate to prevent road debris from entering the toolbox. In order to check if the cooling done by the flywheel fan is sufficient enough, the generator set was run for 90 minutes under low, medium and high load conditions. Loads of 600 Watts, 900 Watts 1500 Watts were set on a portable heater through heater settings of low, medium and high respectively. This accounted for 17%, 25.7% and 42.8% of the rated loss for the APU. During this test, temperature inside the toolbox was recorded every 5 minutes, using a digital thermometer. The thermometer was placed on the bottom surface of the toolbox. Care was taken to not let the tip of the thermocouple touch any surfaces. This particular location of the thermometer was chosen as the alternator of the generator set was discharging hot air into the toolbox at this location. Figure 7 shows the top view 2-D drawing of the location of the thermometer inside the toolbox. Figure 8 shows the front view 2-D drawing of the direction of air flow inside the toolbox due to natural convection process.

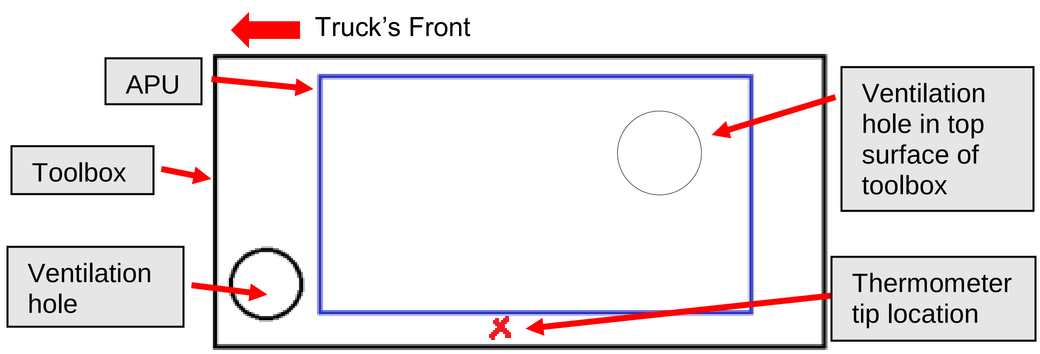


Figure 7: Location of the thermometer inside the toolbox for temperature measurements

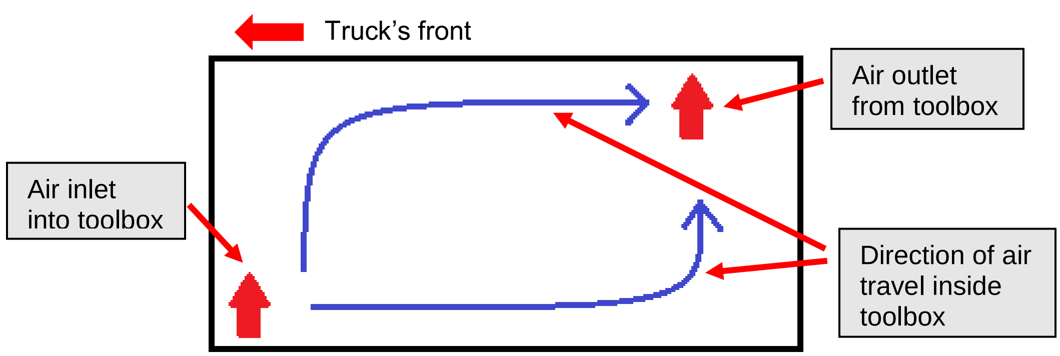


Figure 8: Direction of air flow inside the toolbox due to natural convection

The ambient temperature was recorded to be 12℃. It was observed that the temperature reached approximately 92℃ in total 90 minutes of operation, and was still climbing.

These observations proved that the natural convection along with the flywheel fan cooling the engine, was not sufficient enough to cool the toolbox and an additional fan was required to be installed to cool the APU and toolbox internally. A 120V AC 0.4 Amp rating fan was available at the APS labs. This fan was installed inside the toolbox to observe the temperature drop if any. Figure 9 shows the location of the additional fan and the thermometer inside the toolbox. Figure 10 shows the direction of air inside the toolbox due to the installation of an additional fan.

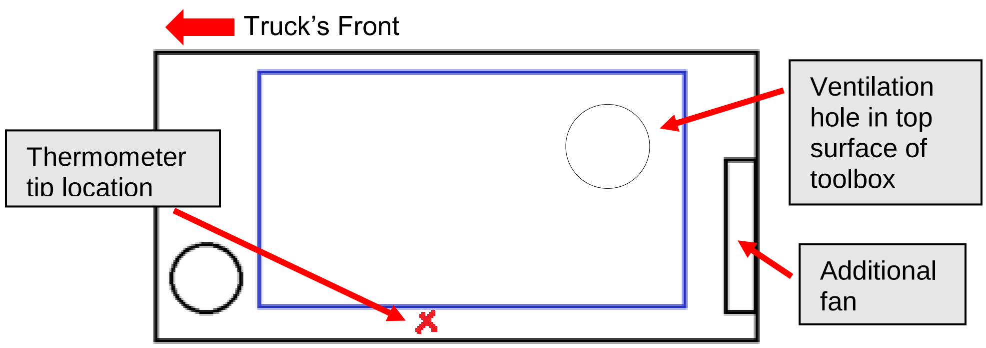


Figure 9: Location of the additional fan and thermometer inside the toolbox for temperature measurements

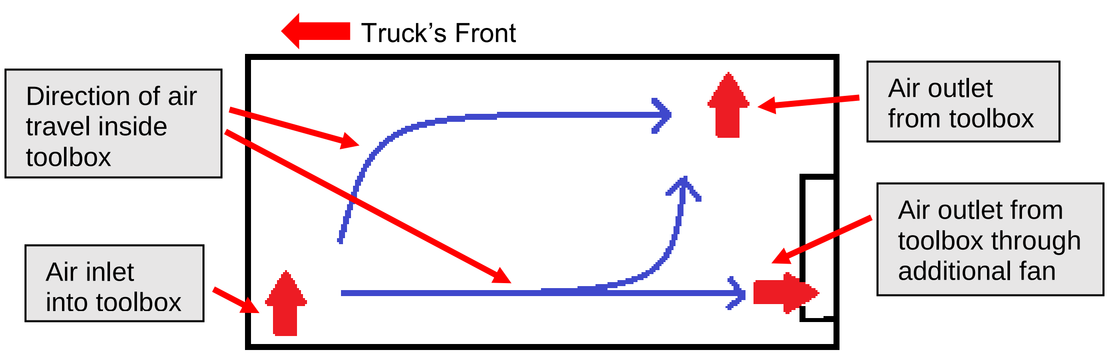


Figure 10: Direction of air flow inside the toolbox due to forced convection

The fan's connections were plugged onto the generator set's control panel. It was intended to start functioning as soon as the APU starts working. The ambient temperature recorded was

17.6℃. Figure 11 shows the plot of the temperature attained inside the toolbox with the additional fan and without it.

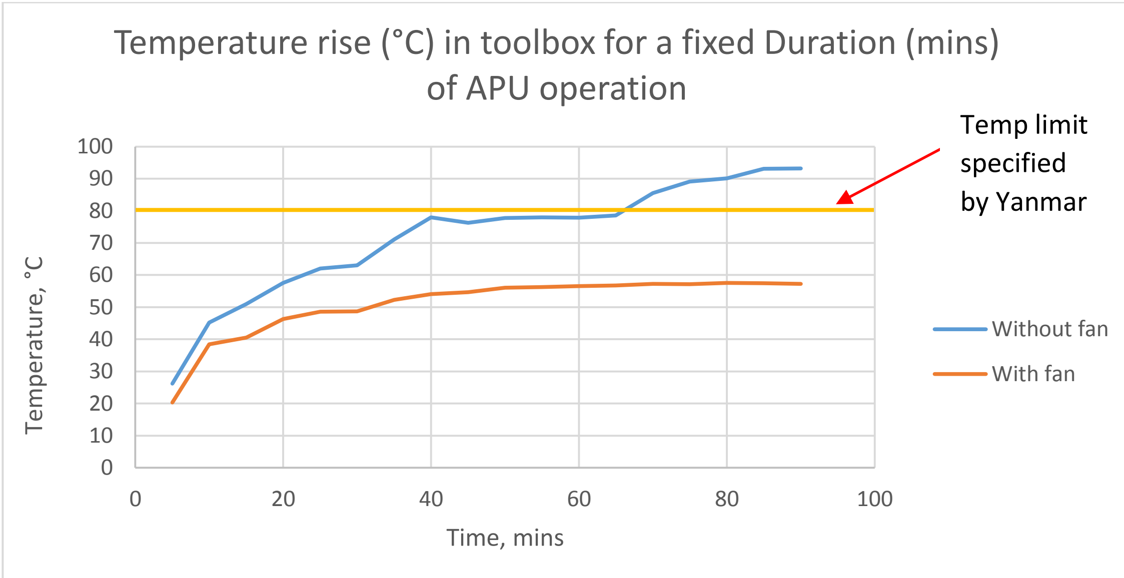


Figure 11: Temperature rise (℃) in the toolbox over duration (mins) of APU operation

As seen from Figure 11, temperatures reached with the additional fan installed, are less as compared to those reached without it. A 38.5% decrease in temperature inside the toolbox was achieved by installing the additional fan. The temperatures inside the toolbox with the additional fan were also below the maximum operating limit specified by Yanmar.

2.3. APU engine exhaust system

One of the sources of noise from an engine is from the sudden expansion of the exhaust gases when they are released from the engine. This is where mufflers come into use. For the silent operation of the APU, it was required to re-design the exhaust system for the APU's engine so as to achieve quiet operation of APU.

2.3.1. Need for a new exhaust system

The APU, when operating at 3600 rpm, produces approximately 93 decibels [7] (dB) of sound at 1-meter distance from the APU. A day-to-day conversation produces approximately 60-70 dB of sound, making the APU 28-30 dB louder than the noise level human ears are used to hearing. As per OSHA, if a person is exposed to sound more than 85 dB continuously [8], this can lead to loss of hearing or other adverse effects. It was thus, very important to curtail the noise emitted by the APU.

Also, as discussed in section 2.1.1, the total width of the APU with the muffler provided by Yanmar is 18 inches. While the available width in the tool box was 16 inches. This additional 2 inches would have let to design and fabrication of a new enclosure for the APU, thereby increasing project time and cost. These reasons led to designing of a new exhaust system for the APU system.

2.3.2. Literature review about mufflers

During the operation of engines, in the fourth stroke, also known as the exhaust stroke, the combusted exhaust gases are pushed out of the cylinder into the exhaust manifold. These exhaust gases are at a very high temperature and pressure. If these come out directly into the atmosphere, they expand suddenly and produce noise, usually above 100dB.

Sound waves are pressure pulses that vibrate the ear drum back and forth and this is perceived by the human brain as sound. These pressure pulses are produced inside the exhaust pipe due to the simultaneous collision and stacking of high pressure exhaust gas molecules with low pressure molecules inside the exhaust pipe. Due to this, a low pressure area is created behind the stack-up of molecules and thus, the sound wave makes it way much faster through the pipe than the gas molecules do [9].

There are three major types of exhaust noise. A pulsating noise is emitted when exhaust gases at high pressure and high temperature are released through the exhaust valves from the cylinders. A flow noise is created by exhaust gas flow in the exhaust pipes. When the exhaust gases flow inside the exhaust pipe, their motion causes eddying, oscillating and impacting of the gases inside the exhaust system and this causes the flow noise. Furthermore, as the exhaust gases exit the exhaust system, a jet noise is created [10].

Mufflers are usually designed in such a way so that they reflect these pulsating and flow sound waves produced by the engine in a very effective way. Inside the muffler, these reflected sound waves are made to cancel each other.

Sound waves have the following characteristics:

- Frequency: The fluctuation of the pressure waves determines the frequency of the sound wave. If the pressure fluctuates faster, it causes high frequency waves and if the pressure fluctuates slower, it causes low frequency sound waves.

- Air pressure level: This determines if a sound wave is loud or soft. The amplitude of the pressure wave reaching the human ear determines the loudness. If the amplitude of the wave is high, the ear drum vibrates more and hence it is concluded that the sound wave is loud and vice versa.

Apart from the above characteristics, two sound waves can be added and subtracted from each other. These properties of sound waves are used in designing a muffler.

- **Constructive Interference:** If two sound waves approaching a human ear are in phase with each other, they add up to give a resultant wave, which is of same frequency but double the amplitude as individual waves and thus the human ear hears the sound. Figure 12 shows the addition of two waves in the same phase and the resultant wave generated.

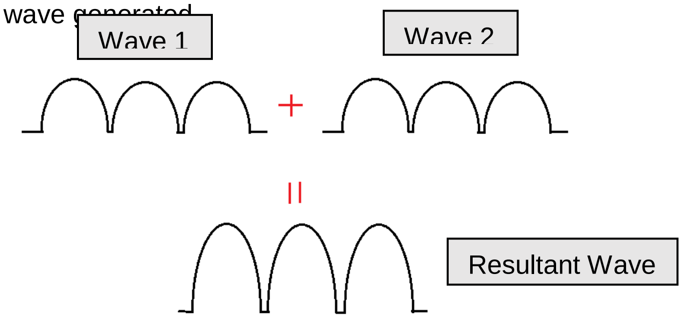


Figure 12:Contructive interference of two waves in the same phase generating a resultant wave with greater amplitude

- **Destructive Interference:** If two sound waves are out of phase with each other, they add up to give a resultant wave with no amplitude and thus the human ear hears no sound at all (Figure 13)

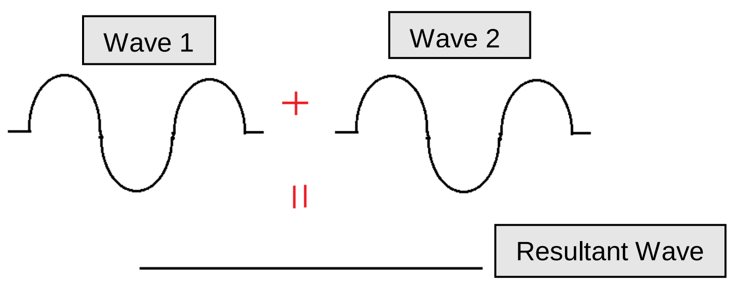


Figure 13: Destructive interference of two waves out of phase with each other, generating a resultant wave with zero amplitude and thus lower sound

Thus, it is utmost important to achieve maximum destructive interference of sound waves in a muffler in order to achieve sound loss. Currently, there are two types of mufflers produced in the industry, which utilize the principle of destructive interference.

Reactive Mufflers: These type of mufflers work on the principle of destructive interference of sound waves. These mufflers consist of multiple resonating and expansion chambers that are designed and fabricated in such a way so as to reduce the sound pressure level at particular frequencies. The muffling is brought about by the sound waves reflecting from the walls of the chamber and canceling out each other [11].

The reactive mufflers perform well when it comes to noise attenuation. However, these mufflers result in high backpressure. Backpressure is defined as the extra static pressure exerted by the muffler on the engine due to the restriction in the flow of exhaust gases through the muffler or exhaust pipe. High backpressure reduces the engine performance by decreasing power and increasing fuel consumption, and hence emissions [12]. Figure 14 shows the cut out view of a reactive muffler.

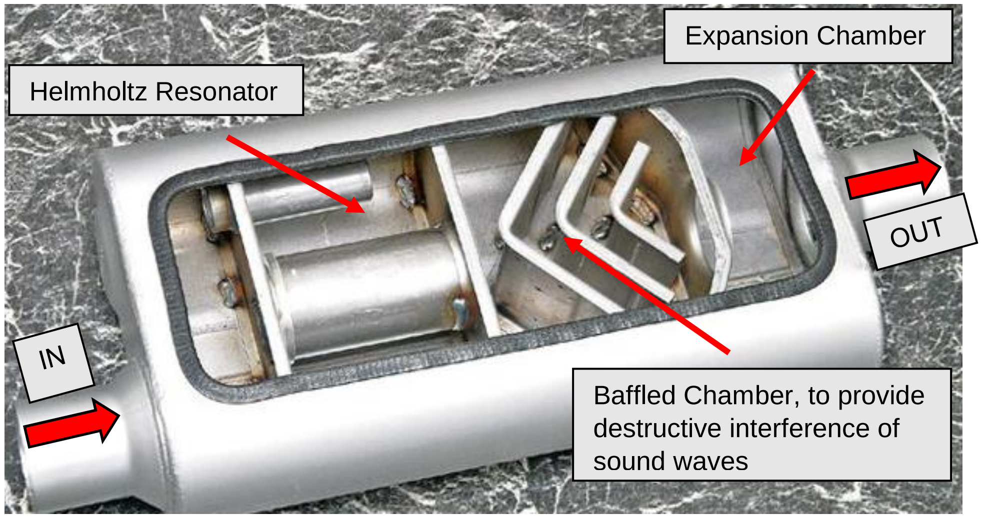


Figure 14: Labelled diagram showing the various chambers in a reactive muffler [13]

Absorptive Mufflers: These mufflers do not have any restrictions to exhaust gas flow and allow free flow of the exhaust gases. The exhaust gases enter from the center of the muffler and pass through a straight pipe with perforations made in it. This straight pipe with perforations is surrounded by a sound absorbing material. Usually steel wool or fiber glass wool is used as the absorbing material. The amplitude of sound waves gets reduced as their energy is converted into heat in the absorbing material. The thicker the absorbing material, the better the muffling action achieved [14]. These mufflers are cheap and produce less backpressure. Hence, these are frequently chosen by automotive users. These are also known as glass-pack mufflers due to the glass wool packing in them. This type of muffler is good in absorbing high-frequency waves coming out from engine exhaust. Also, the longer the glass packed muffler, the better attenuation of exhaust gases. Figure 15 shows an absorptive muffler.

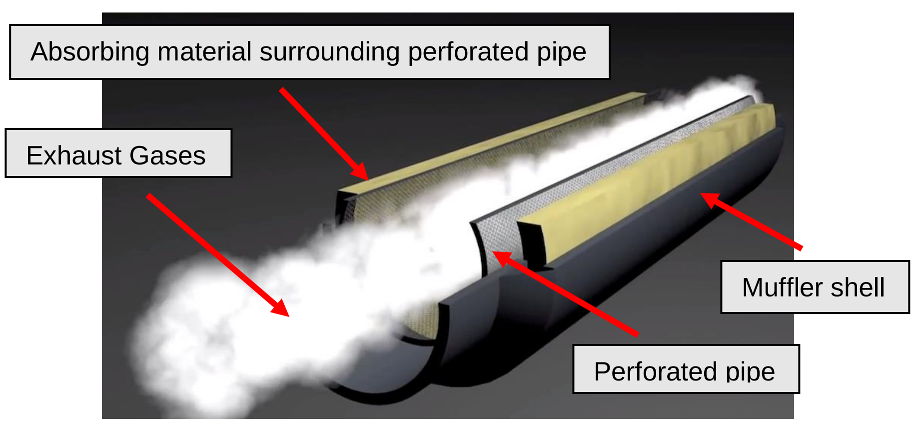


Figure 15: Absorptive muffler labelled figure [15]

Furthermore, a lot of research has been done in the field of mufflers. One such research was done on how the geometrical parameters of the mufflers affect the performance of a reactive muffler. The authors changed the lengths of each chamber to understand how these parameters affect the performance of their cross-flowed perforated and 3-chambered reactive muffler. They concluded that the noise attenuation is directly proportional to the axial length of the muffler. However, due to the restriction of space in modern automobiles, it is important to design low volume mufflers, which in turn also results in low cost. The authors then observed that 30% reduction in length of the rear chamber did not change the performance of the muffler when compared to the base model and also that decrease in the length of the middle chamber prevents cross flow, achieving a greater pressure loss in this particular model [16].

2.3.3. Design with absorptive/glass-pack mufflers

As mentioned in the previous section, the lower the pressure and temperature of the exhaust gases leaving the exhaust system, the lower the noise produced by the gases. The length of the exhaust pipe plays an important role in cooling the exhaust gases, indirectly reducing noise. If the length of the exhaust pipe is long, this allows the exhaust gases to further cool down, reducing the temperature and pressure difference between the exhaust gases and atmospheric air. Also, due to space constraints near the toolbox, it was decided that the exhaust pipe had to be routed from the toolbox to the rear of the truck. This also allowed mounting of mufflers as there was ample space at the rear of the truck, in contrast to the space near the APU.

The Advanced Power Systems Lab had four HMWs donated by the US Army for testing purposes. The testing on this HMWs was completed and their mufflers became available for re-use. Since the mufflers in the HMW were glass-packed mufflers, the first part of APU exhaust testing was done on these, as a measure to eliminate high frequency waves from the exhaust.

In order to estimate the diameter of the exhaust pipes to be used in the exhaust system modelling, it was necessary to know the temperature of the exhaust. A test was conducted to record the exhaust temperatures using a thermocouple. The thermocouple was placed in the mouth of the muffler outlet and the data was recorded in an excel sheet using a LABVIEW program. Figure 16 shows a 2-D drawing of the location where the thermocouple was placed for measurements.

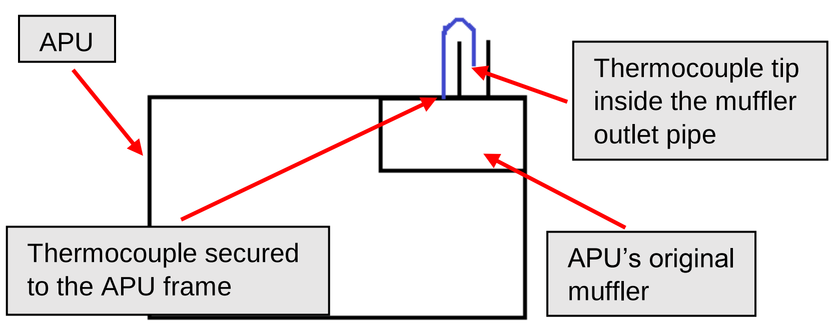


Figure 16: Location of the thermocouple on the APU for exhaust temperature measurements

The plot of the exhaust temperature over time is shown in Figure 17.

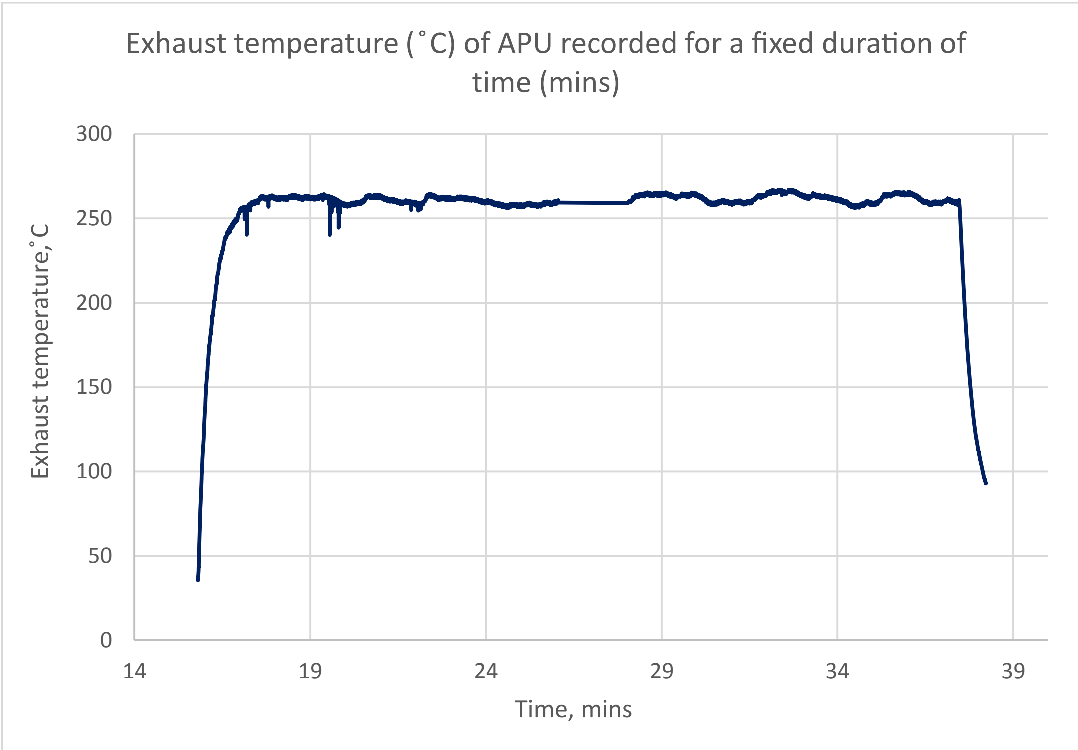


Figure 17: Temperature of the APU engine exhaust (°C) recorded using a thermocouple for a fixed duration of time (mins)

Figure 17 plot shows that on starting the APU, a temperature of 290℃ was reached. However, after the APU operation was stabilized, the maximum temperature that the APU exhaust reached is approximately 260 °C. This temperature was critical in designing the exhaust system for the APU.

In order to decide the exhaust pipe diameter, the values of the exhaust air flow needed to be calculated.

As per the stoichiometric combustion equation, we can write.

$C_{12}H_{23} + 17.75(O_2 + 3.76N_2) \longrightarrow 12CO_2 + 11.5H_2O + 66.74N_2$

Fuel consumption = 0.42 gallons/hr.
Diesel in Liters = Gallons x 3.785 liters/gallon = 0.42 x 3.785 = 1.5897 liters

Also, 1 liter = 1000 cm^3

Density of Diesel = 0.832 kg/liter

$Mass\ of\ Diesel\ (grams)\ =\ Diesel\ in\ Liters\ x\ Density\ of\ Diesel$

= 1.5897 x 0.832

= 1.322 kg

= 1322.63 grams

Now, looking at the diesel fuel combustion equation,

$$Moles\ of\ Diesel\ =\ \frac{Mass\ of\ Diesel}{(12\ x\ Mol.mass\ of\ C) + (23\ x\ Mol.mass\ of\ H)}$$

$$= \frac{1322.63}{(12\ x\ 12)+(23\ x\ 1)}$$

= 7.92 moles of diesel

Now, moles of exhaust produced per mole of diesel:

$$Moles\ of\ diesel\ x\ \frac{(12+11.5+66.74)\ Moles\ of\ exhaust}{1\ mole\ of\ Diesel} = 7.92 \text{ x } 90.24$$

= 714.7 moles of exhaust

We can now calculate the volumetric exhaust flow rate using ideal gas equation as:

V = (nRT)/P (Assuming pressure at the end of exhaust as 1.1 bar)

V = (714.7 x 8.314 x 533) / 110000 m^3/hour

= 28.79 m^3/hr

= **0.479 m^3/min**

Thus, the volume flow rate of exhaust gases coming out of the APU is 0.479 m^3/min. Now, let's calculate the exhaust pipe diameter required for this exhaust flow rate.

According to a modified form of Darcy's equation,

$$\Delta P = 4 \text{ x } f \text{ x } (\rho) \text{ x } \frac{L\ x\ v\ x\ v}{2\ x\ g\ x\ d} \qquad (1)$$

Where,

ΔP = Pressure drop, bar

f = Darcy's co-efficient, dimensionless

ρ = density of air at 260 degrees Celsius, kg/m^3

L = length of pipe, m

V = velocity of gas flow inside pipe, m/s

g = acceleration due to gravity, m^2/s

d = diameter of pipe, m

we can also write the above equation as:

$$\Delta P = 4 \times f \times (\rho) \times \frac{L}{2 \times g \times d} \times \left(\frac{Q}{A}\right)^2$$

This equation reduces to:

$$d = \left[\frac{4 \times f \times \rho \times 2 \times L \times Q \times Q}{g \times \Delta P} \right], \text{m}$$

$$= \left[\frac{4 \times 0.08 \times 0.675 \times 2 \times 0.508 \times 0.479 \times 0.479}{9.81 \times 10000} \right] \text{m}$$

= 0.016 m
= **0.66 in**

Thus, we can conclude that a 1 1/2” diameter pipe, which was easily available in the lab inventory, will hold good for the exhaust system. Hence, the new exhaust system was constructed keeping in mind a 1 1/2” diameter pipe.

A computer aided design of the exhaust system was made in order to see how the assembly would look and to check the safety of the system. The exhaust gases, after coming out of the engine’s exhaust valve are routed to the rear end of the truck. They passed through two glass packed HMW mufflers in series. Figure 18 shows the front view of the exhaust system. Figure 19 shows the full view of the exhaust system.

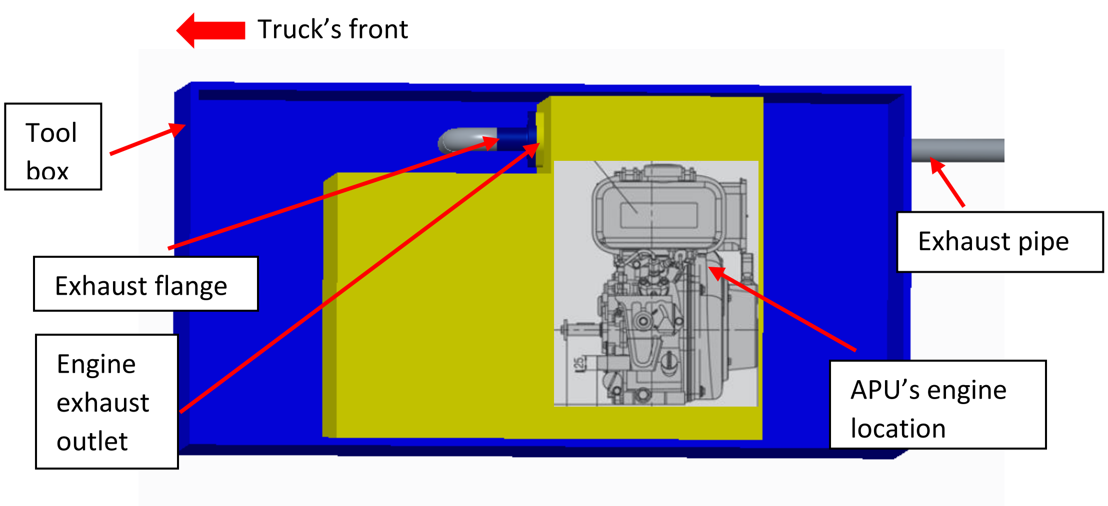


Figure 18: Location of the APU’s engine in the toolbox. Exhaust pipes routed from the engine to the rear of toolbox, finally to rear of truck.

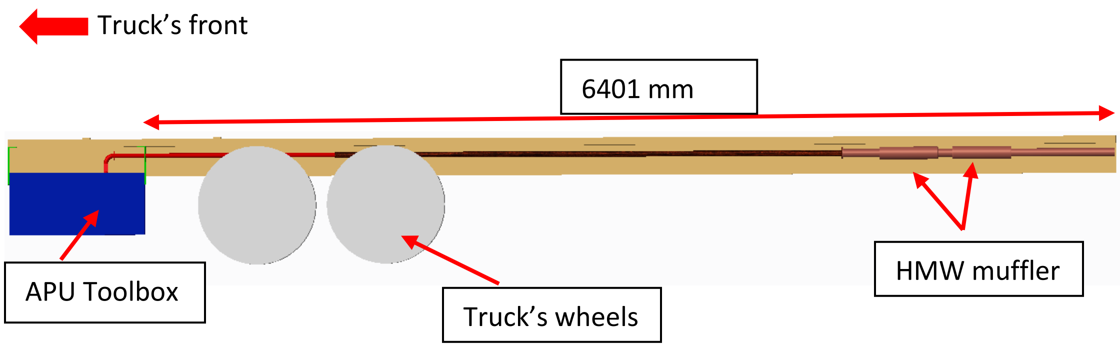


Figure 19: Front view of computer aided design for the exhaust system with the HMW mufflers

The exhaust pipes travelling from the APU to the rear of the truck had to pass very close to the truck's wheels. This was due to space constraints to route the exhaust pipe to the rear of the truck. Figure 20 shows the front looking back view of the entire exhaust system.

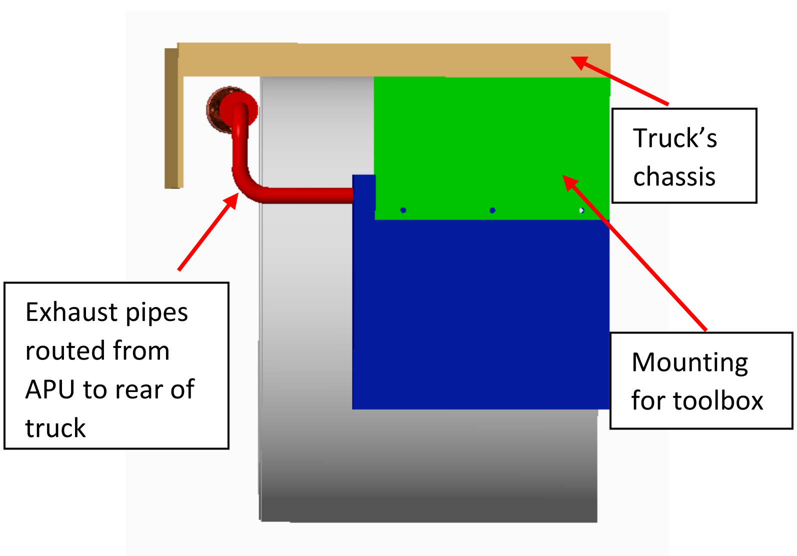


Figure 20: Front looking back view of computer aided design for new exhaust system for APU

Figure 21, below, shows the various components involved in the exhaust system for the APU.

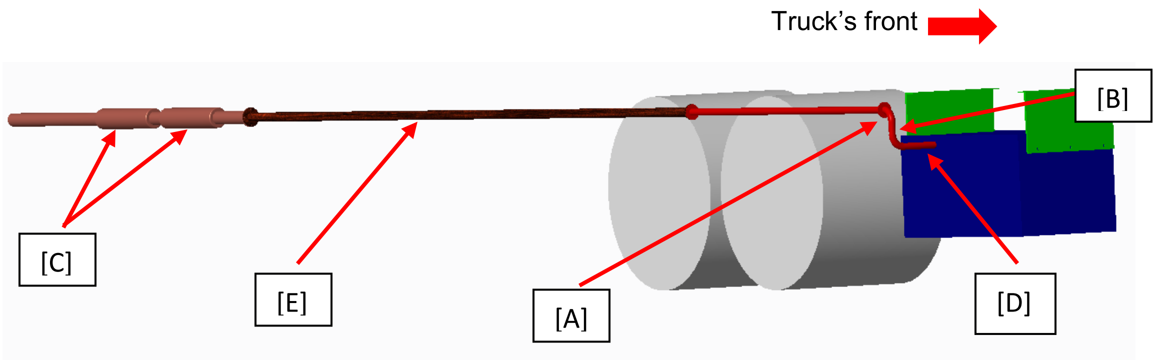


Figure 21: Labelled figure of the components in APU's new exhaust system

From Figure 21, the various components involved in the exhaust system are:

- [A] – Elbow bend
- [B] – Straight pipe, neck piece
- [C] – Humvee mufflers (2 nos.)
- [D] – Straight pipe, from engine exhaust manifold
- [E] – Straight pipe, extension pipe

As per the design, it was decided to weld the pipes together to prevent any leakage of exhaust gases during APU operation. The entire assembly was planned to be mounted on the truck's chassis by automotive style exhaust hangers, as shown in Figure 22.

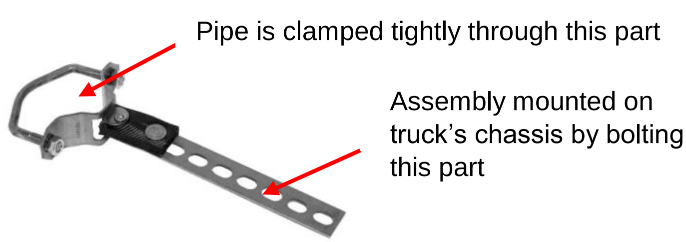


Figure 22: Automotive style exhaust hangers [31]

2.3.4. Fabrication of the exhaust system with glass-pack mufflers

The space available to mount the glass pack mufflers at the rear of the truck was 4200 mm x 762 mm (L x W). The overall length of the glass pack mufflers was 1473.2 mm and overall width was 406.4 mm. Figure 23 shows a 2-D drawing of the space available to mount the mufflers and the space occupied by the mufflers.

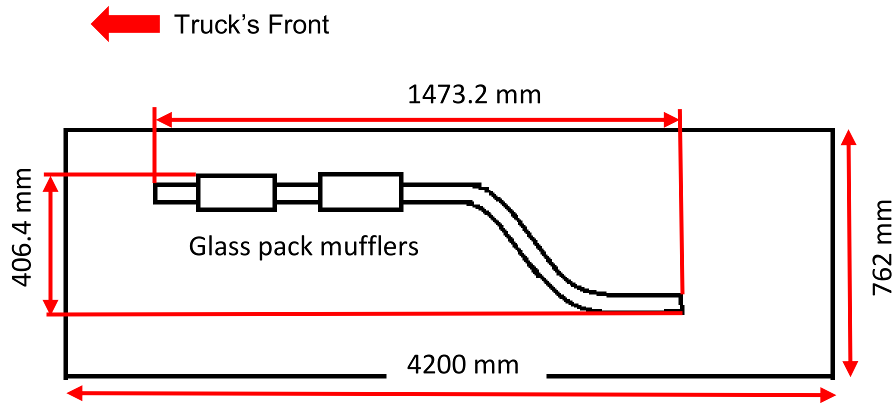


Figure 23: A 2-D drawing top view of the space available to mount the glass pack mufflers at the rear of the truck

From Figure 23, it was clear that there was ample space available to mount the glass pack mufflers at the rear of the truck's chassis. The fabrication of the exhaust system with glass pack mufflers required a review to check the components availability in the APS labs. The APS lab's pipe inventory had several 1 1/2" diameter pipes available. Upon removing the mufflers from the Humvees, it was realized that they had 2" bore diameters. Even though pipes with 2" diameter were also suitable for the entire assembly, it was decided to use the 1 1/2" diameter pipes. This was because there was very little clearance space between the truck's chassis and wheels, from where the pipes had to travel from APU to the rear of the truck. Also, as the pipe sizing calculations, a 1 1/2" was sufficient for this project's requirement and a 2" diameter pipe would have led to unnecessary increase in cost.

In order to weld the system with different pipe diameters, suitable pipe adapters were used to reach a uniform size of 1 1/2". Humvee mufflers was welded to the system at the rear of the truck, as seen in Figure 24.

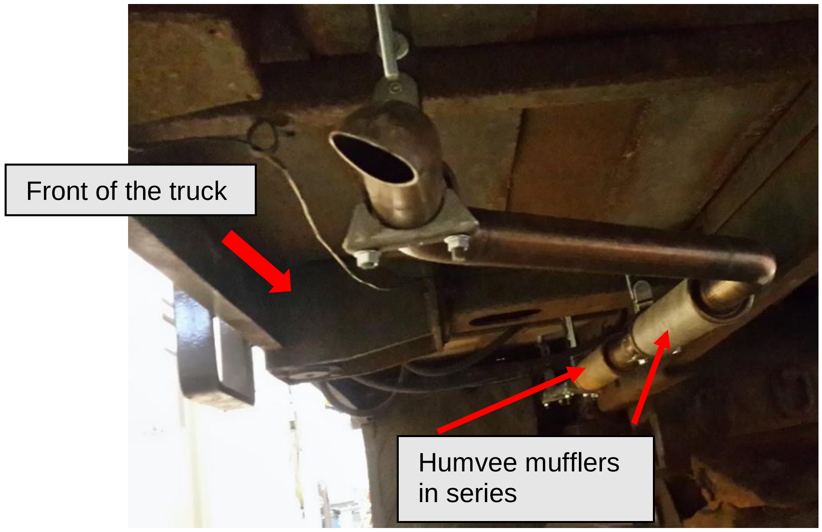


Figure 24: New exhaust system for the APU with two glass pack mufflers mounted in series

The pipes and muffler assembly was fastened on the truck's chassis by automotive style exhaust hangers. The hangers were spaced out uniformly so as to balance the weight of the system. In the section of the exhaust system where the pipes were close to the truck's tires, additional exhaust hangers were used to prevent the contact of the pipe with the tires. Figure 25 shows the exhaust hangers holding the exhaust system.

Figure 25: Automotive style exhaust hangers used to fasten the new exhaust system to the chassis of the truck

While mounting the exhaust system assembly on the truck, a downward slope was given to the assembly. This was done so as to provide a path for the water, formed from condensed vapor, to flow out of the exhaust system.

2.3.5. Design of APU's exhaust system with a reflective muffler and glass-pack mufflers

The APU, with the glass pack mufflers, was tested for noise. A Mastech MS6300 Digital Multifunction Environment Meter was used to measure the sound in decibels. Noise was recorded using the 'decibels' function on an environment multi-meter. This sound measurement test was conducted inside the APS labs. Figure 26 shows the location in which the sound measurements were made.

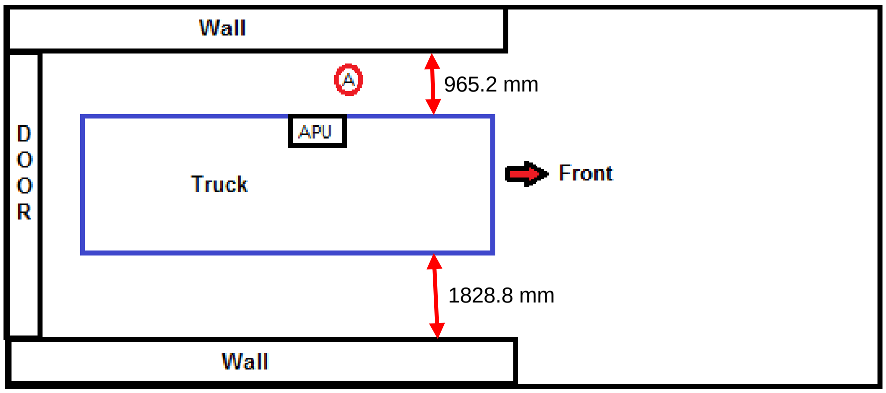


Figure 26: 2-D top view of the location where the sound measurement for APU operation with glass pack mufflers was made

The sound measurement was done at location A as shown in Figure 26. The sound measured was 100 dB, which was louder than the sound made by the APU with the stock muffler. One of the reasons for this loud sound was due to the closed box structure of the room as seen in Figure 26. In a closed room, the sound waves do not get a path to escape and hence collide against each other and the room walls. This collision of sound wave particles with adjacent air particles causes them to vibrate too. These constant collisions lead to higher vibrations and hence, a louder sound. It was hypothesized that the sound measurements for the same exhaust system would be slightly quieter outside the lab due to the availability of a greater medium for the sound wave particles to lose their energy to and hence reduce their vibrations.

This noise was still very loud as compared to the OSHA standards mentioned in the last section. Since the glass pack mufflers, tested for attenuating high frequency sound waves, did not perform any significant sound attenuation, it was decided that a reflective muffler was to be used to attain sound attenuation.

A Chevrolet Silverado muffler was available for testing. This muffler is a four chamber muffler which was estimated to carry out both high frequency and low frequency muffing. The high frequency muffling was to be brought about by the glass wool packing over the perforated pipe chamber. The low frequency muffling was to be brought about by the resonator chambers and in many cases, by a chamber containing baffles. Figure 27 shows the cut off image of the Silverado muffler used in this project. Figure 28 shows the approximate dimensions of the chambers inside the muffler and the air flow through the muffler.

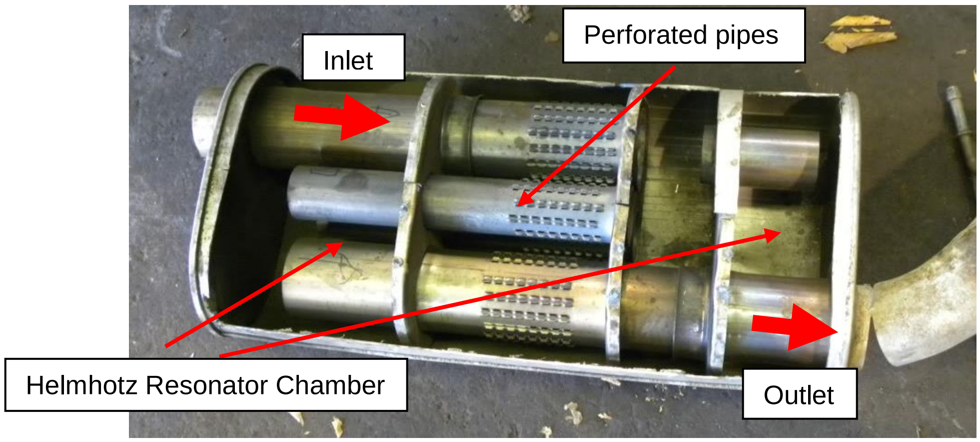


Figure 27: 2003 Chevrolet Silverado muffler cut-off [18]

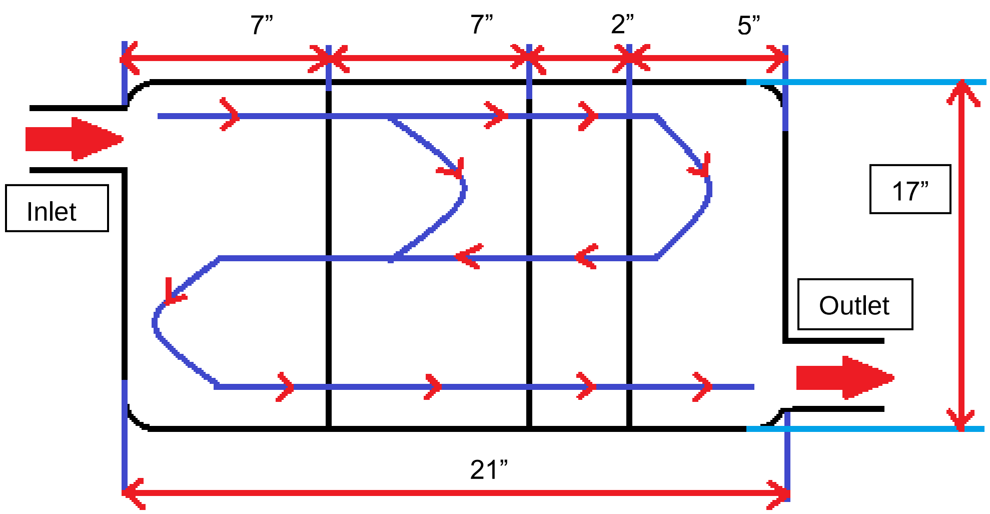


Figure 28: Approximate dimensions of the length of the chambers inside the muffler and direction of exhaust gas flow inside the muffler

The exhaust gases enter the muffler from left side (marked by the arrow). The first chamber acts as a Helmholtz resonating chamber where the low frequency waves are partially attenuated. The gases then enter the second chamber which consists of perforated steel tubes. These are covered by high temperature acoustic material, which attenuates the high frequency waves. The third chamber provides baffling action to the gases and the fourth chamber again acts as the Helmholtz resonating chamber again. The dimensions of the Helmhotz chamber are calculated so that the waves reflected by the resonator help cancel out certain frequencies of sound in the exhaust.

This reflective muffler was coupled in series to the glass packed mufflers so that both low frequency as well as high frequency waves were muffled off. A computer aided design of the entire assembly is shown in Figure 29.

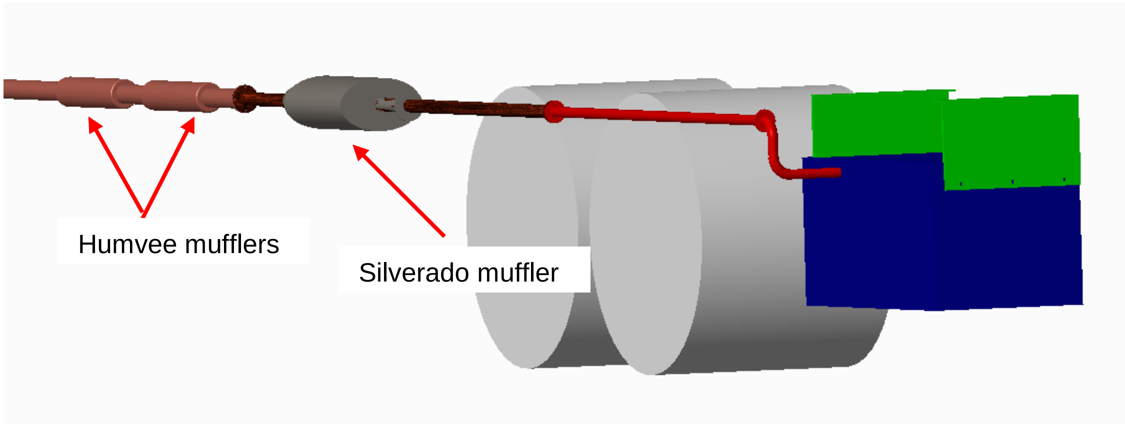


Figure 29: CAD drawing of APU's exhaust system with Silverado and HMW mufflers

2.3.6. Fabrication of the APU's exhaust system with reflective and glass-packed mufflers

The reflective muffler's dimensions are 21" x 12 1/2" x 7 1/2" (L x W x H). With the current exhaust system assembly, there wasn't any space available after the glass-packed mufflers, to mount the reflective muffler. Thus, an exhaust pipe section before the glass-packed mufflers, had to be removed.

The reflective muffler had a bore diameter of 2 3/4". Suitable adapters were used to step down the diameter to 1 1/2". The reflective muffler, with stepped down bore diameter size, was installed in the exhaust system, in series with the glass-packed mufflers. Exhaust hangers were used to hold the muffler to the truck's chassis. The APU's exhaust system now consisted of a reflective muffler and two glass-pack mufflers to attenuate low and high frequency sound waves. Figure 30 shows the APU's exhaust system with reflective and glass-packed mufflers.

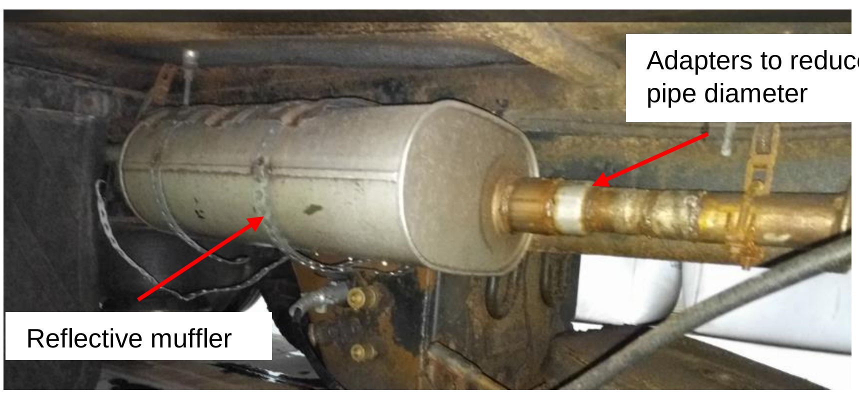


Figure 30: APU's exhaust system with a reflective muffler in series with glass-packed mufflers for noise attenuation

2.4. Auxiliary Fuel Tank

The APU's location made it eligible for two solutions for fuel supply to the APU. One solution was inserting a T-joint in the truck's fuel supply line from the main fuel tank and routing a fuel line to the APU. The other solution was installation of a new fuel tank explicitly for the APU itself. The former solution eliminated the need for an additional fuel tank explicitly for the APU, thus saving money. But it would lead to truck being immobile if any changes were to be made in the APU fuel system in future as the main fuel line to the truck's engine would also need to be replaced due to the T-joint in it. The latter solution ensured that the APU fuel system would be completely independent and would not affect the truck's operation.

Furthermore, the lowest level of fuel in the truck's main fuel tank was approximately 390 mm lower than the APU. It was necessary to check the maximum negative head that the fuel can be at for the APU to draw fuel from it. A fuel level test was conducted to determine this.

2.4.1. Fuel level test for APU operation

The APU in this project, came with a 1.7-gallon fuel tank. Figure 31 shows a flowchart of the fuel flow from the fuel tank to the engine.

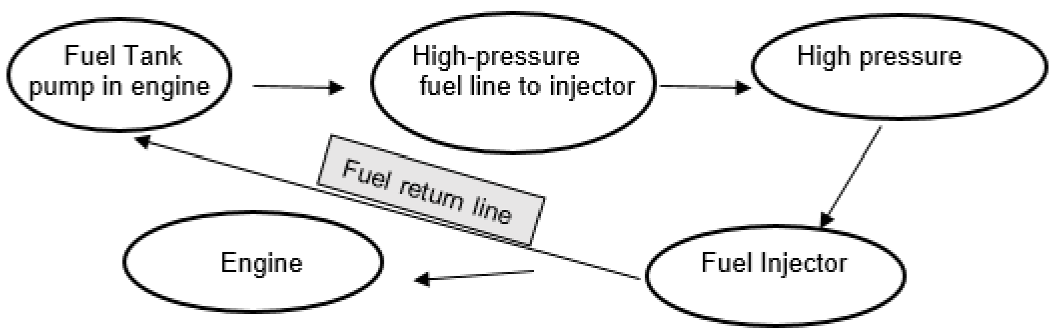


Figure 31: Flowchart showing the path the fuel travels to reach the APU's engine

The fuel from the APU's original fuel tank flows to the engine under gravity. As per the original configuration of the APU, the fuel tank was located at 454.025 mm from the ground. The APU's engine has a mechanically operating fuel pump. The fuel pump's operation is controlled by the camshaft of the engine. The fuel tank was mounted at a distance of 161.925 mm above the fuel pump.

As per the stock condition, the fuel level in the APU's fuel tank always had a positive head. If the truck's main fuel tank was to be used, the APU's engine would not have a positive head once the fuel level was 40% of the original fuel level in the tank. This would require the driver to maintain the truck's fuel tank capacity above 40% every time the APU was to be operated. Figure 32 shows the schematic 2-D view of the various heads available for the APU fuel pump.

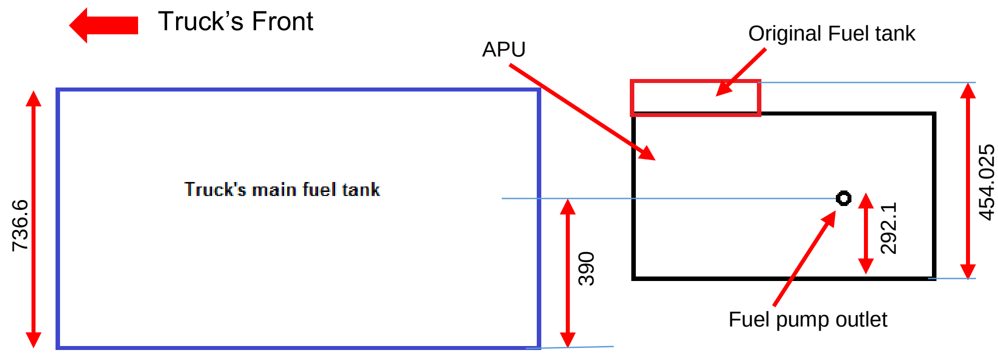


Figure 32: A 2-D schematic on the fuel heads for the APU's fuel pump.

Therefore, to determine the negative head that the pump will draw fuel from, this test was conducted. Figure 33 shows the test set-up for the fuel level test.

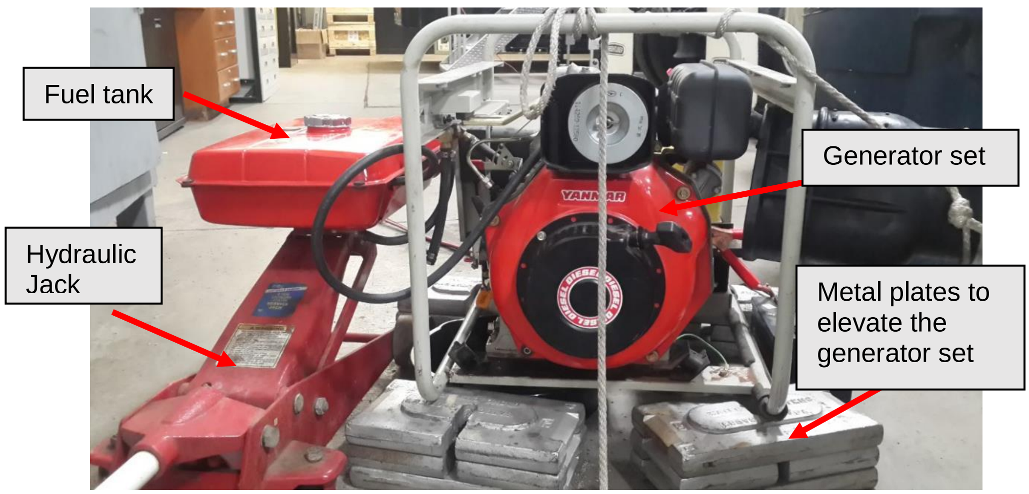


Figure 33: Set-up for fuel level testing to determine lowest fuel level for APU operation

The fuel tank was mounted on a hydraulic jack to obtain different heights for fuel tank and operation of the APU at these fuel tank height levels was observed. Metal plates, available in the APS labs, were used to elevate the APU above the ground level so as to increase the span of testing.

Various test runs were done on the APU. Fuel level test was carried with the fuel tank elevated to a height it was originally mounted onto on APU's frame, till the lowest height APU would stop working at. 'Pass' indicated the APU firing and running and 'Fail' indicates the APU failing to run. Table 5 shows the observations noted down from this test.

Sr. No.	Fuel head from fuel pump (mm)	Test Results
1	154.725	Pass
2	46.775	Pass
3	27.725	Pass
4	-10.375	Pass
5	-64.35	Pass
6	-131.025	Pass
7	-169.125	Pass
8	-173.35	Pass
9	-190.25	Pass
10	-204.5	Fail
11	-200.725	Fail
12	-197.5	Fail
13	-195.525	Fail
14	-194.525	Pass

Table 4: Observations recorded from fuel level test

In Table 5, in column 2, negative values indicate the distance below the outlet valve of fuel pressure pump. The APU ran flawlessly for different height levels till the fuel tank was lowered to a height of 190 mm below the engine's fuel pump (including 190 mm). When the fuel tank was lowered further to 204.5 mm below the fuel pump, the APU stopped working. The fuel tank was then raised higher slowly till it started working again. At a distance of 194.525 mm below the fuel pump, the APU started working. This suggested that the base of the fuel tank should not go beyond 194.525 mm below for efficient APU operation.

As mentioned before, the original fuel tank provided by Yanmar had a capacity of only 1.7 gallons. Even though Yanmar claims that the APU would last for 6-15 hours once the tank was full [19], it would lead to filling up of the generator's fuel tank every night before parking the truck at a rest stop.

Hence, for this project, it was economical and beneficial to use a new fuel tank explicitly for the APU. The new fuel tank could be mounted keeping in mind the fuel tank level constraints. The fuel line connections from the new fuel tank to APU would also be different from the main fuel line, reducing the risk of effecting truck operation.

2.4.2. Selection of a location to mount the new fuel tank

Before selecting the location for the new fuel tank, following constraints were to be considered:

- It should be close to the APU
- It should allow fuel flow via gravity to the APU
- Driver should be able to re-fuel it easily
- Fuel tank and lines to be away from rotating components

Keeping the above constraints in mind, the following locations were shortlisted: -

Location 1 – Next to the truck's toolbox (Figure 34)

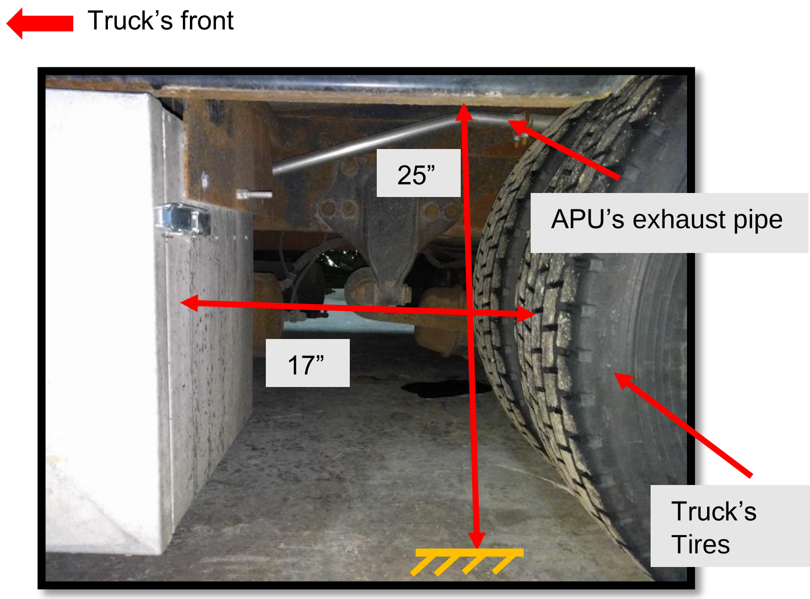


Figure 34: Location 1 for selection of locations to mount the new fuel tank. In between APU and truck's wheels

Advantages:

- Near the APU
- Fuel flow possible under gravity

Disadvantages:

- Near the tires. The truck's tires lose threads at times. Hence not safe.
- Exhaust pipe very close to fuel tank

Location 2 – Between truck's fuel tank and battery cover (Figure 35)

Truck's front

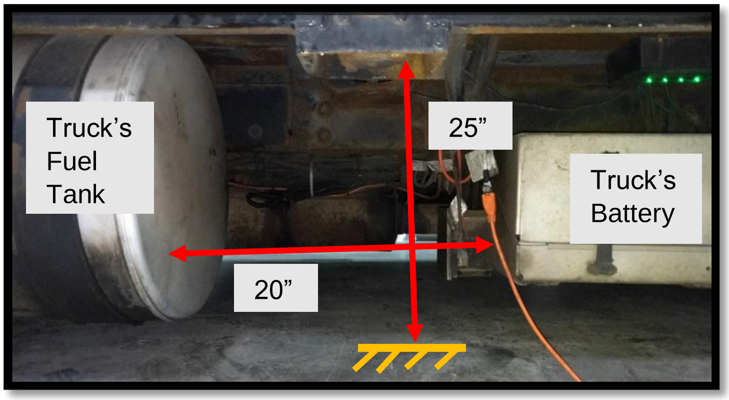


Figure 35: Location 2 for locations to mount the new fuel tank. In between truck's fuel tank and truck's battery case

Advantages:

- Near the APU
- Fuel flow under gravity possible
- Close to truck's fuel tank. Hence ergonomically perfect location

Disadvantages:

- Close to truck's batteries

Location 3 – Opposite side of truck near the truck's air compressor reservoir (Figure 36)

Truck's front

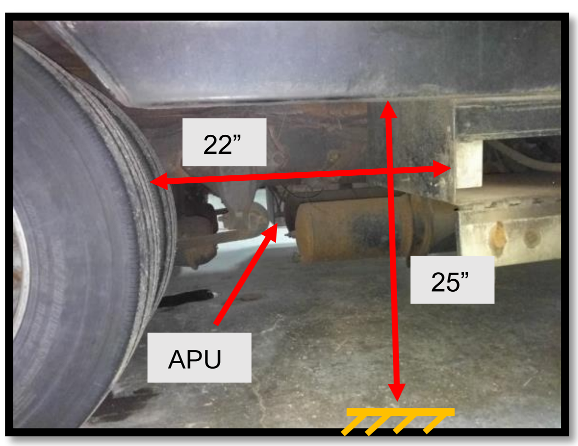


Figure 36: Location 3 for mounting of new fuel tank. Opposite side of APU near truck's air compressor reservoir tank.

Advantages:

- Ample horizontal space available

Disadvantages:

- Near the truck's tires
- Far from the APU
- Fuel flow via gravity would not be efficient due to lesser head and greater fuel line distance
- Fuel hoses need to travel perpendicular to driveshaft of the truck, making it a potential for contact

Looking at the above locations and their advantages and disadvantages, it was decided that location 2 was the best possible available location to mount the fuel tank due to aesthetic, ergonomic and safety point of view.

2.4.3. Selection of a Fuel Tank

Once the location for the new fuel tank was decided, the dimensions of the location were measured and a new fuel tank for the APU was to be selected. Following were the constraints for selecting the auxiliary fuel tank:

1. Available dimensions are 20" x 34" x 25" (l x b x h)
2. Maximum distance of fuel level should be 14.5" below chassis to permit fuel flow to the pump
3. Capacity should be at least 5 gallon
4. Proper venting in the fuel tank required
5. 2 outlets desired, one for fuel supply and 1 for fuel return from the engine
6. Material of the tank should sustain various environmental and road conditions
7. Ease of refueling the fuel tank
8. Minimum cost

Following the above constraints, several fuel tanks were identified from a wide variety of tanks available in the market. Table 6 highlights the various tanks considered and their properties:

Sr.	Company	Capacity	Dimensions (lxbxh)	Cost	Photo

No.	Name	(gallons)	(in inches)	(in USD)	
1	Yanmar (original generator set fuel tank)	1.7	18 x 13 x 14.5	Free	
2	RJS Drag Racing Fuel Cell [20]	5	13 x 12.88 x 8.25	109	
3	RJS Drag Racing Fuel Cell [21]	8	19.75 x 14.63 x 7.5	128	
4	RJS Drag Racing Fuel Cell (upright) [22]	8	13 x 9 x 17	150	

Table 5: Fuel tank properties for selection of auxiliary fuel tank for APU

As per previous discussions, the original Yanmar fuel tank was of low capacity and was hence discarded from the review. The 8-gallon fuel tank (No. 3) was 19.75” long and the space available was 20” in length. It would fit very tightly in this space and clearance space would be really less. The 8-gallon upright fuel tank (No. 4) had a height of 17” from the chassis. Mounting this tank would violate the constraint number 2, which states that the base of the tank should be 14.5” from the truck’s chassis for efficient APU operation. The 5-gallon fuel tank, however, conforms well within the dimensions of the available space. 5-gallon capacity would also power the APU for 18 – 44 hours as compared to the 6-15 hours with a 1.7-gallon fuel tank.

Due to the above mentioned reasons, the 5-gallon tank (No. 2) would serve this project’s purpose the best. The other advantages of this fuel tank are:

- Standard recessed plastic cap, with a vent hole on the top. This provides efficient venting to the fuel tank.
- The fuel tank is made of cell foam which can sustain rough environment and temperature conditions.
- The tank has 2 outlets (-8 AN)
- Tip over valve (-6 AN), to which the fuel return line can be connected.

2.4.4. Design review of new fuel tank

To validate the fitment of the new fuel tank in the selected location on the truck's chassis, a computer aided design was made. Figure 37 shows the fuel tank in the selected location on the truck's chassis.

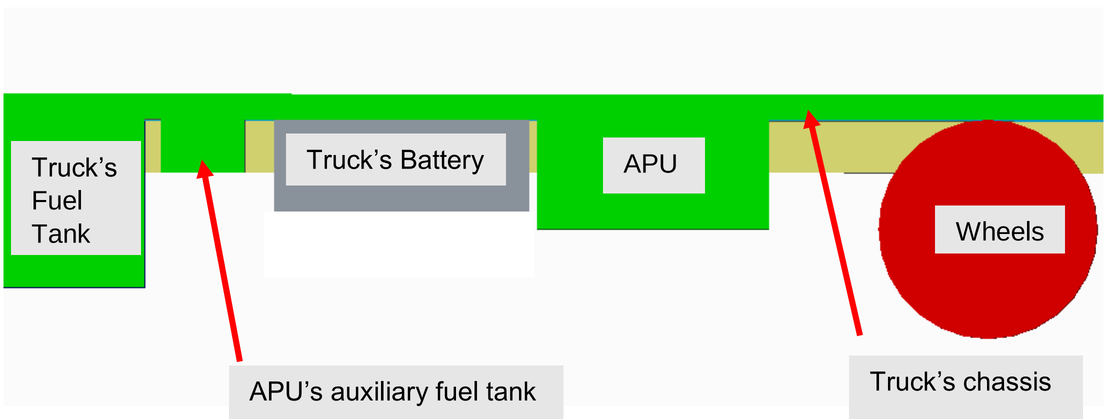


Figure 37: Computer aided design of the APU's new fuel tank in a location between the truck's fuel tank and battery box

From Figure 37, it is seen that the 5-gallon fuel tank is a perfect fit in the location 2, i.e. between the truck's fuel tank and battery enclosure. It can also be seen that ample clearance space is available between the truck's fuel tank and battery case.

2.4.5. Fabrication for mounting the new fuel tank

An arrangement had to be made in order to suspend the fuel tank from the chassis. The new fuel tank was required to be suspend from the chassis as the fuel tank cap was at the top of the tank and a clearance space for re-fueling was required. Furthermore, the base of the tank had to be restricted to within 14.5" from the truck's chassis so as to allow operation of the APU.

Thus, measurements were made accordingly and small metal uni-struts were cut out in order to suspend the tank from the chassis. Steel plates were welded on both ends of the uni-strut bars so as to mount the bars to the truck's chassis on one side and mount the fuel tank on the other side.

In order to mount the fuel tank on the uni-strut bars, a fuel tank mounting strap was installed. This strap was fuel tank specific. The strap along with the fuel tank was mounted on the uni-strut at four points. Figure 38 shows the entire assembly used to mount the fuel tank on the truck.

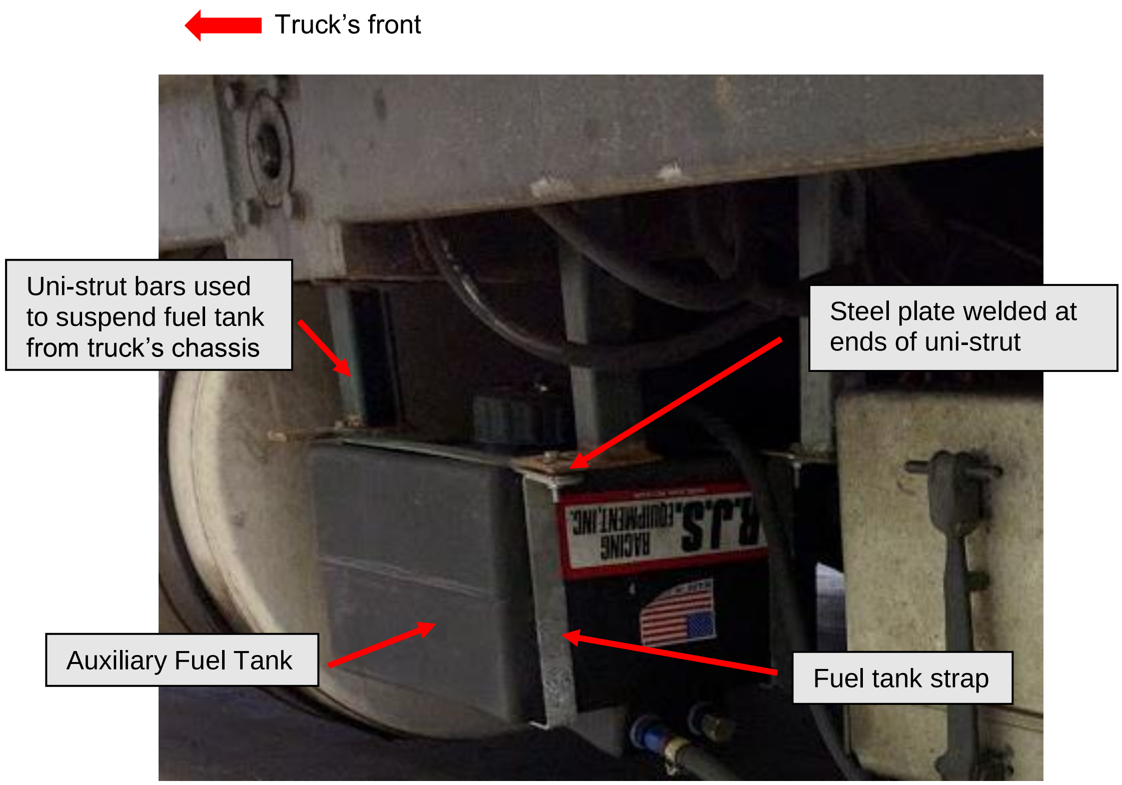


Figure 38: Fixture to suspend the new fuel tank from truck's chassis

The auxiliary fuel tank has three fuel outlets, two -8 AN outlets in the front and one -6 AN outlet near the fuel tank cap. Out of these three outlets, one -8 AN outlet was sealed using a cap nut. The other fuel outlet required a special fitting that screwed into the -8 AN JIC outlet on one side and had a barbed fitting on the other end, where the fuel hose could be connected.

The fuel hose size required was 1/2" I.D. whereas the special fitting that converted the -8 AN outlet to barbed fitting allowed a hose of 3/4" I.D. Thus, appropriate pipe fittings and adapters were used to convert the fuel pipe size from 3/4" I.D. to 1/2" I.D. The engine also has a fuel return hose that flows from the injector back to the fuel tank. This hose was connected to the -6 AN fitting of the fuel tank.

As an additional feature, a boat primer was installed in the fuel inlet line so as to prime the system in case the APU was started after a long duration. In order to prevent the fuel lines from hanging loose between the fuel tank and the APU and to adhere to the DOT guidelines, the fuel lines were clipped to the outer cover of the battery box using a C-clip. Figure 39 shows the fuel tank connections to the APU.

Truck's front

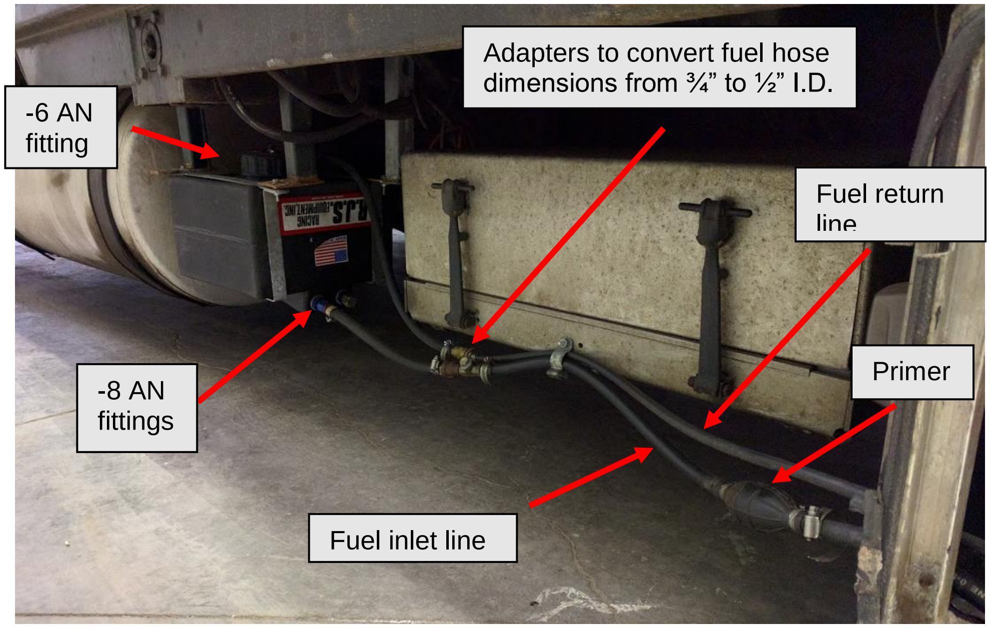


Figure 39: Fuel line connections between the fuel tank and APU

2.5. Electrical connections

One of the functional requirements of this project is starting and stopping of the APU from the truck's cabin. Charging of the truck's batteries and providing electrical supply inside the truck's cabin to run a portable heater/cooler to maintain suitable HVAC conditions were also to be facilitated. Accordingly, electrical connections had to be made from the APU to the truck's cabin to power the 12V and 120V electricals. Also, electrical connections were needed from APU to the outside of the APU box for charging truck's batteries and running the block heaters. The next few sections discuss the electrical connections made to and from the APU to achieve these requirements.

2.5.1. Starter switch

The APU is equipped with a key operated electric start feature. There were two solutions available to facilitate starting and stopping of APU from inside the cabin. One solution was by installing a new toggle switch inside the cabin and other was by removing the starter switch from the control panel of the APU and installing it inside the cabin. The former solution would lead to accessing the generator set from inside the cabin as well as outside the cabin. It also would require duplicating the starter switch wiring connections. The latter solution would just require extending the current connections to the truck's cabin.

In order to test the toggle switch in this system, an OFF-ON-(Mom) ON toggle switch was installed in the system. In order to use the toggle switch by duplicating the solenoid starter switch connections, the starter switch was required to be in 'Always ON' position. This is because the electric starter has a built-in solenoid, which requires a 12V DC supply to activate it. Without the solenoid activated, the APU cannot start as there will be no power in the circuit.

This requirement of having the solenoid switch turned ON before using the toggle switch to start the APU would require the driver to manually turn it on every time the APU was to be operated. This would violate the requirement of starting/stopping the APU from truck's cabin. Furthermore, if the driver ever forgot to turn off the starter switch on the APU panel once the APU was turned off with the toggle switch, the starter switch could possibly contribute to unnecessary draining of truck's battery.

Due to the above reasons, it was decided to remove the starter switch from the APU control panel and mount it inside the truck's cabin.

2.5.2. Selection of location to mount starter switch in truck's cabin

There were two locations where the starter switch could be mounted inside the truck's cabin:

Location 1: On the truck's dashboard (Figure 40)

Figure 40: Location 1 inside truck's cabin for mounting the starter switch

Advantages:

- Electrical wires can be routed easily

Disadvantages:

- If the starter switch is mounted on the dashboard, the issue of unavailability of location for mounting a 120V AC electrical outlet will arise
- If driver wants to shut of APU while on the rest bed, the switch would be out of reach and the driver would have to get up to reach it

Location 2 – Overhead panel above the driver's resting bed (Figure 41)

Figure 41: Location 2 inside truck's cabin for mounting the starter switch

Advantages:

- Easily reachable
- Allows ample space on dashboard to mount the 120V AC electrical outlet

Disadvantages:

- Routing of wires is complex as compared to previous location as the wires have to be routed inside the cabin walls in order to reach the overhead panel.

Considering the advantages and disadvantages for both the locations, it was decided that the starter switch would be mounted in location 2, i.e. on the overhead panel in the truck's cabin.

2.5.3. Wiring diagram for starter switch connection in truck's cabin

Figure 42 shows the wiring diagram of the starter switch routed from the APU control panel to the truck's cabin.

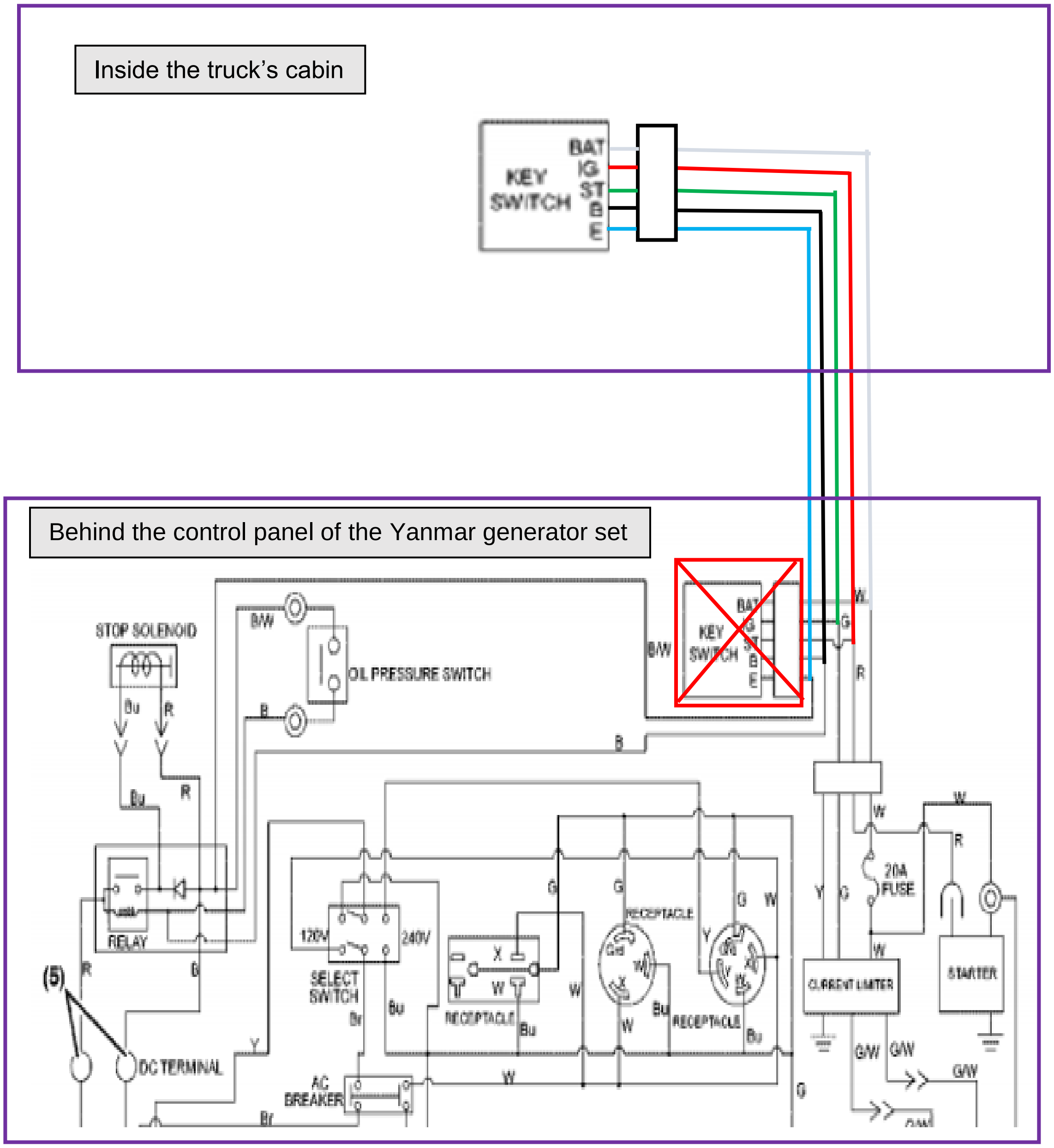


Figure 42: Wiring schematic of APU starter switch connections to truck's cabin [23]

As seen from Figure 42, the wire connections that were originally connected to the starter switch on the APU control panel were cut. It was decided that new wires with same color code were to be used so as to maintain standardization. The wire size of the wires which were used to make the original connections were studied. They were 14 gauge wires. Since the APU came with these wires, it was estimated that the starter switch needs approximately 10-12 Amps of current. Since the new connections required the wires to travel approximately 30-40 feet from the APU control panel to the truck's cabin, it was necessary to check the gauge size required for carrying 10-12 Amps of current over that long distance. Figure 43 shows the gauge size of wires for different current carrying requirements.

#4 and above = Cable
1/0 and 2/0 are Service cable

120V (US) (@ 80% max load)
(50ft run or less)

Gauge	Amps	Watts
#16	9	1080
#14	12	1440
#12	16	1920
#10	24	2880
#8	32	3840
#6	40	4800
#4	48	5760

Figure 43: Gauge size of wires for different wire current carrying capacities for 50 feet run [24]

From Figure 43, it can be seen that for 10-12 Amps of current, a 14-gauge wire is sufficient for a run of 50 feet. This project required maximum 40 feet run, making a 14-gauge wire size apt for the starter switch wire connections.

2.5.4. Fabrication of electrical connections for starter switch

The electrical wiring connections going to the starter switch on APU's control panel were cut, and the starter switch was removed from the APU control panel. New 14 gauge wires were connected to the cut off wires and the new wire connections were routed to the front of the truck via truck's chassis. These wires were shielded in a corrugated split tubing and fastened to the chassis and other wire bunches using zip-ties. Figure 44 shows the wires being routed to the front of the truck, via chassis.

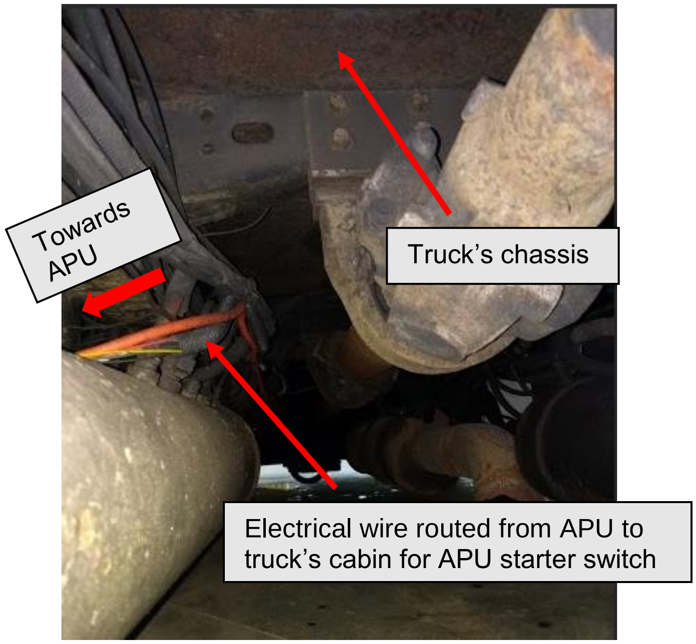


Figure 44: Electrical wire connections for starter switch routed from APU to the truck's cabin from via truck's chassis

These wires could enter the truck’s cabin from either the left side or from right side. Careful observations were made towards the electrical wiring connections on both sides. Figure 45 shows the front of the truck on the right side from where the wires could be routed into the cabin.

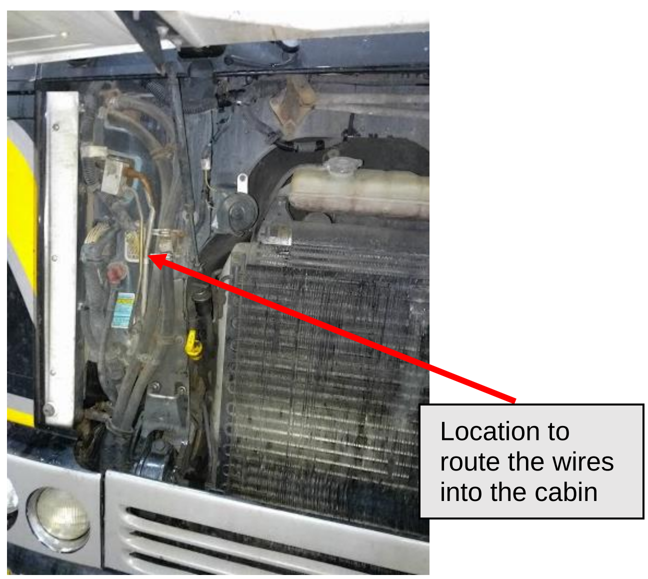


Figure 45: Entry port #1 for wires from the APU to the passenger side of truck’s cabin

This port of entry into the truck's cabin could not be used as all the holes from where the wires enter the cabin were filled. Figure 46 shows the front of the truck on the left side, from where the wires could be routed in.

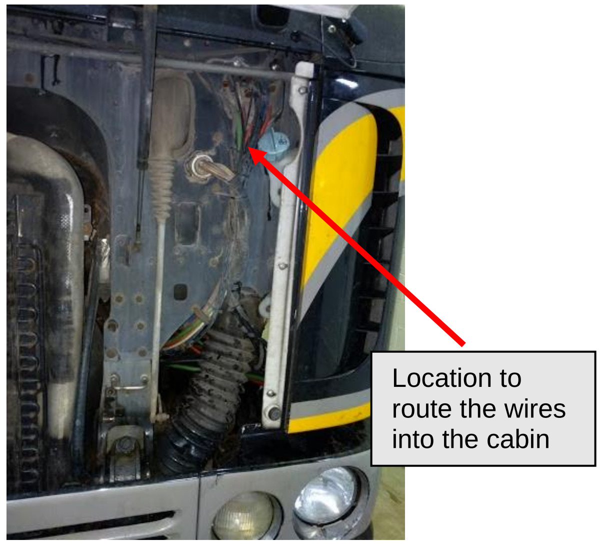


Figure 46: Entry port #2 for wires from the APU to the driver side of truck's cabin

From Figure 46, this port of entry for the wires was very advantageous. This was due to the availability of holes to insert the wires into the cabin. This location was also close to the overhead panel, the location where the switch was to be mounted, thus requiring lesser length of wires for routing. However, it was decided to study the space available on the other side (i.e. inside the cabin) of this entry port first. Figure 47 shows the area available behind the entry port #2.

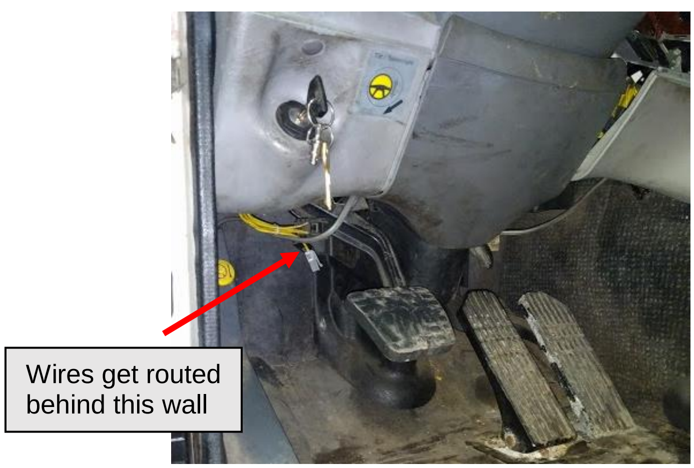


Figure 47: Opposite side of entry port #2 to route wires from APU into the truck's cabin

From Figure 47, it can be seen that wires after entering the truck's cabin from entry port #2 are routed behind a cabin wall. Even though this location would have been the best location to route the wires through as mentioned before, the entire display panel of the truck would have had to be removed to route the wires to the overhead panel. Thus, the plan of using this location to route wires into truck's cabin was discarded.

A final point to route the wires was from an entry point on the right side. Figure 48 shows the wires being routed in the cabin from this port of entry.

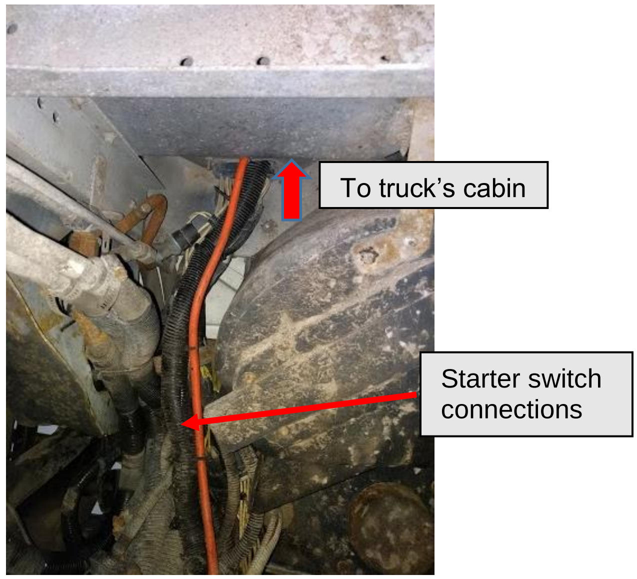


Figure 48: Electrical wires from the APU entering the truck's cabin after being routed underneath the truck's chassis, through entry port #3

Once the wires were inside the truck's cabin, they were routed carefully behind the driver's seat and passenger's seat, over the floor under the driver's resting bed, to the overhead panel above the bed. Figures 49 and Figure 50 show the wires being routed inside the cabin to the overhead panel.

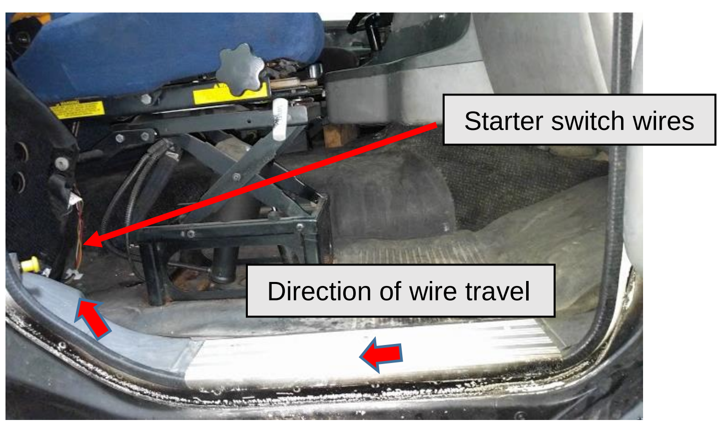


Figure 49: Starter switch wires being routed to the overhead panel in the truck's cabin

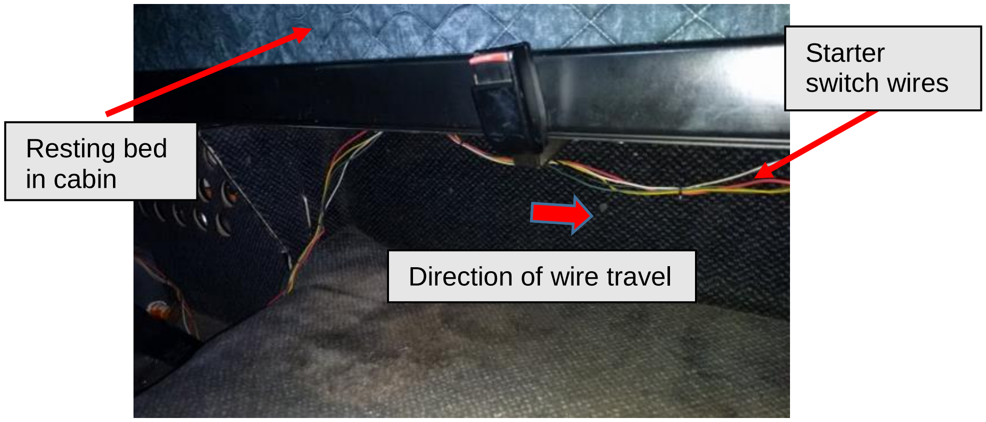


Figure 50: Starter switch wires being routed to the overhead panel inside the truck's cabin

A hole pertaining to the size of the electrical switch mounting screw was drilled and the switch was installed on the panel. Figure 51 shows the starter switch mounted on the overhead panel in the truck's cabin.

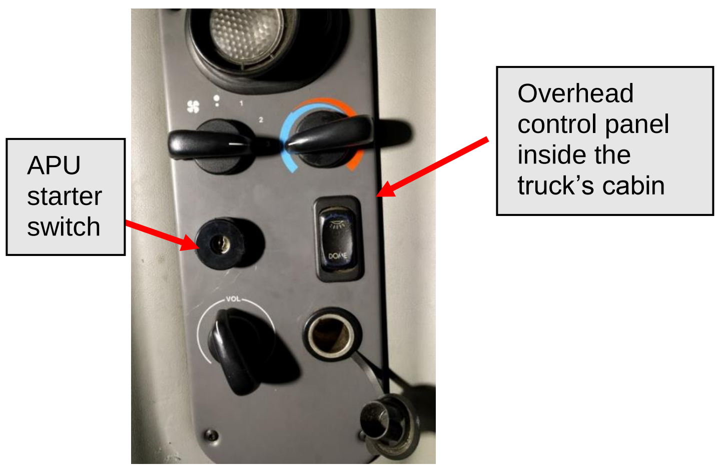


Figure 51: APU starter switch installed in the overhead panel inside the truck's cabin

All electrical connections were made using crimped type connectors. Additional electrical insulation tape was added over the crimped type connectors to ensure the additional safety.

2.5.5. 120V AC outlet connections to truck's cabin

As per the functional requirements of the project mentioned before, a portable heater/cooler was required to be run inside the truck's cabin. In order to validate the connections for the new electrical outlet inside truck's cabin, a portable cabin heater was used. As this particular heater required 120V AC power supply for operation, it was important to have an outlet with the same supply inside the truck's cabin.

The APU has a total of 4 outlets which could be used for providing 120V AC supply. Figure 52 shows the display panel of the APU with the available outlets highlighted [23].

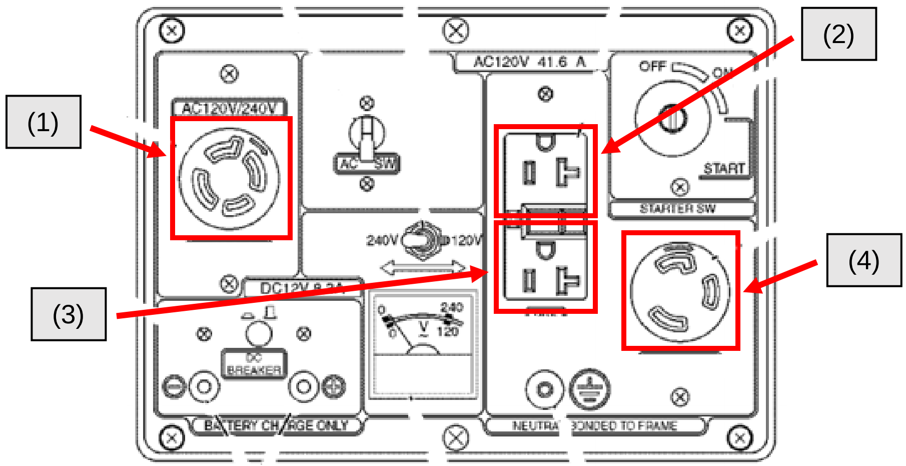


Figure 52: Display panel of the APU with the available outlets highlighted
(1)-120/240 VAC outlet supplying 20.8A; (2) & (3)-two outlets 120 VAC supplying 15A each; (4)-120 VAC outlet supplying 30A

The portable heater inside the truck's cabin would require a maximum of 12-13 Amps. From Figure 52, it was determined that outlets labelled 2 and 3 would act as the best place to access the 120V AC power supply from, to the truck's cabin. These outlets were the best choice as these allowed a maximum current of 15 Amps each. Thus, utilizing the 20.8 Amps (outlet 1) or 29.2 Amps (outlet 4) outlet on the APU panel would be unnecessary as the outlet inside the cabin would never run any device requiring more than 15 Amps of current. Moreover, the outlet's 1 or 4 could be used to charge the truck's batteries or run the truck's block heater as those applications require greater current. Table 7 gives the rating of each of the 4 outlets marked in Figure 52 and also shows the approximate current that will be drawn from each outlet.

Outlet No.	Voltage (V AC)	Current (Amp)	Appliance(s) to be connected	Total current drawn from appliance to be connected (Amps)
(1)	120/240	20.8	-	-
(2)	120	15	Portable heater/cooler, Ventilation fan	15
(3)	120	15	Open to external applications	-
(4)	120	29.2	Battery charger, block heater	20

Table 6: List of outlet ratings and approximate values of ratings of appliances that will be connected to outlets

There were two possible ways to power the 120V AC outlet inside the truck's cabin from outlets 2 or 3 on the APU panel. One way was to cut the connections to the outlet on the APU panel and connect new wires and run them to the outlet in the truck's cabin. The other way was to connect one end of a long extension cord into the APU outlet and connect the other end of the cord to the outlet inside the truck's cabin. The latter way was chosen as this would make the outlets of the APU available to other electrical applications too, other than exclusively powering the outlet in the cabin. An extension cord was chosen instead of separate wires as the extension cord is well insulated and easy to route as compared to separate wires.

The 120V AC connection from APU to truck's cabin were targeted at handling a maximum of 15 Amps current at any point of time. Hence referring to Figure 43, which showed the wire gauge sizes for different current carrying capacities, for 15 Amp current, a 12-gauge size wire was recommended. However, after safety considerations, extension wires for 20 Amp current capacity were purchased.

2.5.6. Wiring schematic for connections to truck's cabin

Figure 53 shows the wiring diagram for powering the 120V AC outlet in the truck's cabin from the APU control panel [23] [25].

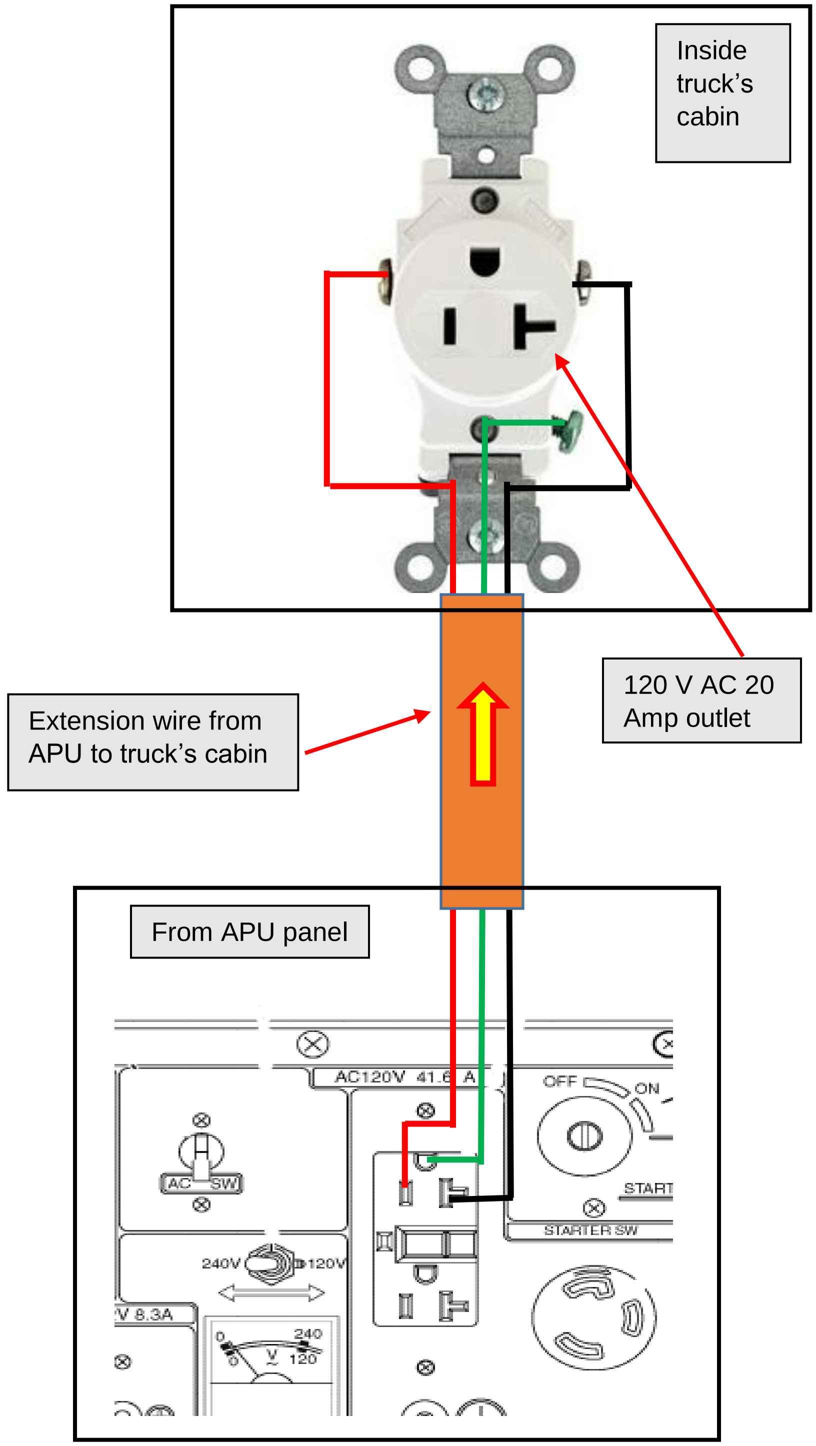


Figure 53: Electrical wiring schematic for powering the 120V AC outlet inside the truck's cabin

2.5.7. Fabrication of wiring diagram for 120VAC outlet to truck's cabin

Referring to Figure 52 above, the 120V AC 15 Amps outlet on the APU's control panel was decided to use to power the electrical outlet in the truck's cabin. An extension cord capable of conducting 15 Amps of current was purchased. One end of the extension cord was plugged into the APU's outlet.

The extension cord was then routed to the front of the truck the same way the starter switch connections were routed via truck's chassis. Figure 54 shows the extension cord being routed from the APU to the front of the truck via the chassis.

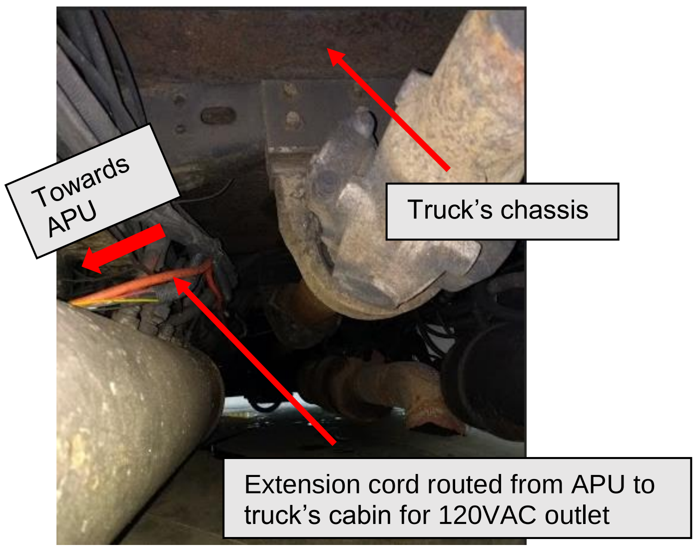


Figure 54: Extension cord routed from APU to the front of the truck via chassis of the truck

The extension cord was also inserted into the truck's cabin the same way the starter switch connections were inserted. The only ergonomic location to mount the electrical outlet inside the truck was in the dashboard of the truck. This was because the overhead panel in the cabin was fully occupied with other switches and outlets. And the electrical wires could easily be routed behind the truck's dashboard.

Once the extension cord was inside the cabin, a few sections of the dashboard were dismantled and the cord was routed behind the truck's dashboard to the location where the electrical outlet was to be mounted. Figure 55 shows the extension cord routed to the electrical outlet on the dashboard.

Figure 55: Extension cord routed from APU to the truck's dashboard

A hole was drilled in the dashboard and the electrical outlet was installed. Thus, whenever the APU was on, the electrical outlet will be receiving voltage and can be used to run portable heater/cooler. Figure 56 shows the electrical outlet installed in the truck's dashboard.

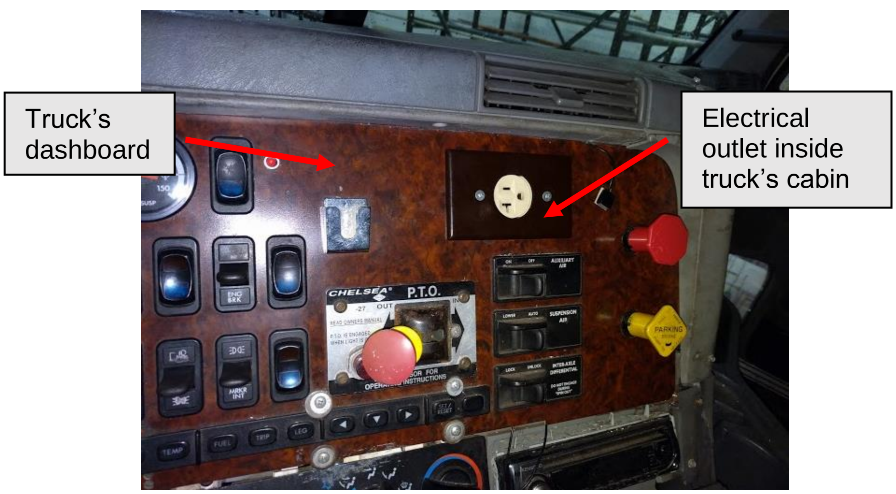


Figure 56: 120VAC electrical outlet mounted on the truck's dashboard.

2.5.8. 120V AC outlet connections to toolbox outlet

The truck's batteries were required to be charged due to the following reasons:

- The APU uses the batteries to start initially
- To start the truck
- To operate the 12V accessories inside the truck's cabin

If ever the truck had issues starting the big engine due to low SOC of truck's batteries, the APU was likely to start and charge and it would charge the truck's batteries. It was thus decided that an outlet from the control panel of the APU would be used to supply power to charge the truck's batteries.

The truck had a four port battery charger which was installed on the truck's chassis, above the battery enclosure. This battery charger had a 3-pin power cord. This charger is currently used to charge the truck's batteries when the truck's engine is turned off.

There were two solutions available for using the battery charger with the APU. One solution was plugging the charger's 3-pin connector directly into the 15 Amp outlet of APU. The second solution was installation of an outdoor outlet on the APU's mounting box and providing electrical connections from APU's outlet to it. The battery charger would then be plugged into the outdoor outlet.

The former solution was discarded because the battery charger's cord length was not sufficient to reach the outlet on the APU. Connecting the battery charger to the 15 Amp outlet on the APU would then leave only 2 outlets for the truck's block heater cord. These remaining outlets required a twisted 3-pin or 4-pin connector, which was not suitable for the block heater. The latter solution, however, would accommodate both the battery charger and block heater using a single outlet of the APU. Hence, it was decided to install an outdoor outlet on the APU mounting box.

The battery charger approximately needed 4-5 Amps for operation and it was estimated that the truck's block heater would require maximum 15 Amps of current for operation. Thus, a 120V AC and 20 Amp outdoor electrical outlet was installed on the toolbox and connections were given to it from the 120V AC 29.2 Amp outlet on the APU's display panel. The 29.2 Amp outlet on the APU's display panel was chosen because if the battery charger and block heater were plugged in together at any time in future, a total of 20 Amps would be drawn from the APU. A 15 Amp outlet cannot serve this purpose then. Also, in order to facilitate a 20 Amps current through the wires, 10 wire gauge size wires were to be used to make the connections.

Usually, for outdoor connections, a GFCI outlet is used. GFCI outlet stands for Ground Fault Circuit Interceptor. This basically trips off if it senses that the current is flowing in a path other than the normal designated current path. This works on the principle of comparison of the current that flows from the live or hot wire and the current that's returned through the neutral wire. If the currents are not equal, the GFCI fuse trips off and the circuit is open.

In this project, a GFCI outdoor outlet was initially installed on the toolbox. However due to the battery charger inductance, the GFCI outlet tripped frequently. Thus, it was decided that the GFCI outlet be replaced by a normal electrical outdoor outlet.

In order to prevent any road side dirt or debris from damaging the electrical outlet, it was decided that a hardened plastic cover be installed.

2.5.9. Wiring diagram for connections to APU toolbox

Figure 57 shows the wiring schematic circuit for the outdoor electrical outlet installed on the APU mounting box [23] [25].

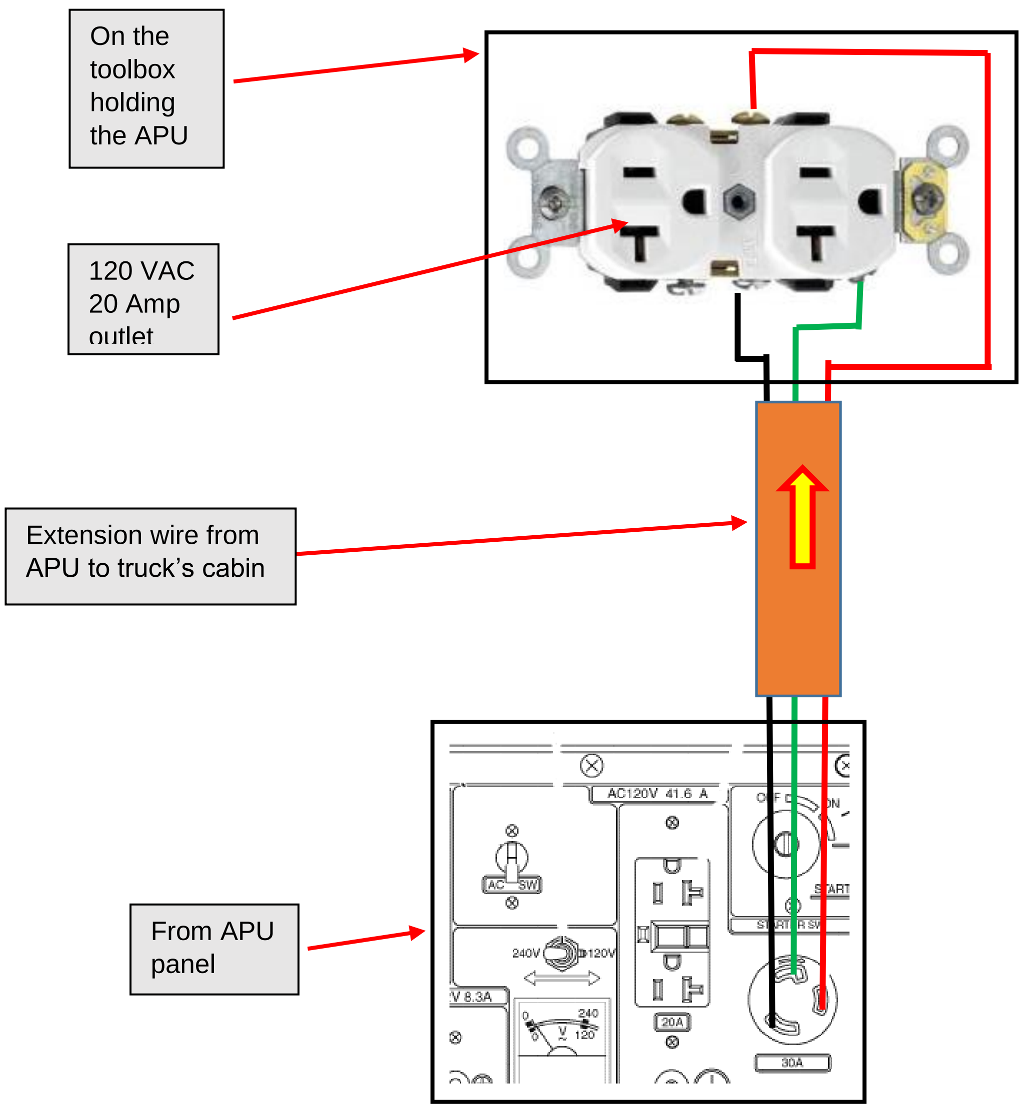


Figure 57: Wiring schematic of the connections from APU control panel to outdoor outlet on toolbox housing the APU

2.5.10. Fabrication of wiring diagram for 120V AC outlet on APU mounting box

Referring to Figure 52 in the last section, the 29.2 Amp outlet (No. 4) was to be used to power the outdoor electrical outlet. An extension cord capable of carrying 30 Amps current was purchased. The electrical outlet was mounted on the APU mounting box. A twisted 3-pin connector was installed on one side of the extension cord and it was plugged into the 29.2 Amp outlet on the APU control panel. The other end of the extension cord was connected to the electrical outlet. A plastic cover was installed over the outdoor switch. Figure 58 shows the plastic cover installed on the APU mounting box.

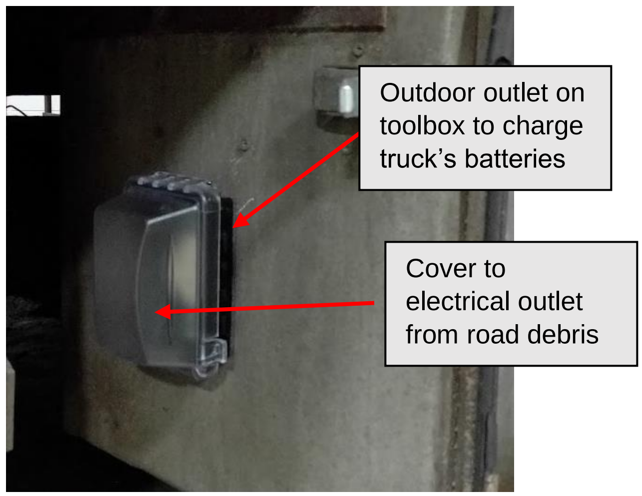


Figure 58: Outdoor electrical outlet installed on the APU mounting box to facilitate charging of batteries and operation of truck's block heaters.

3. REPAIR OF APU

The APU used in this project was a 1990's generator set. It was unused for a long duration of time and hence, the first few tasks were aimed at getting the APU functioning again.

3.1. Fuel Injector Cleaning

Upon cranking the APU for the first few times, it failed to run. The APU service manual was referred to and the possible reasons for it not starting were:

- Air in the fuel line
- Fuel system components damaged
- Fuel injector clogged due to possible dirt in the fuel
- Leaking head gasket

The APU was cranked repeatedly in order to remove the air in the fuel lines. A combustion easy start spray was sprayed into the air intake manifold in order to provide initial combustion. This spray enters the combustion chamber and makes the fuel/air mixture more combustible, which makes the engine fire more quickly. It also contains lubricating oil to protect the engine and prevents wear. After injecting the starter spray through the air intake manifold, when the APU was cranked, it started for a split second and stopped again. The fuel system components were visually inspected for damage. However, no significant damage was observed.

The above validations helped narrow down the problem to either a clogged injector or a blown off head gasket. Before removing the cylinder head and checking the head gasket, it was decided to check the fuel injector for clogging. This was because the former would consume more time as compared to the latter. Also, if the head gasket got damaged during inspection, it would require additional costs to buy a new head gasket.

Fuel injectors are mechanical devices that are responsible for spraying or injecting the correct amount of fuel into an engine in order to have a suitable air/fuel mixture for most favorable combustion. Fuel injectors have a micro fine nozzle hole through which a fine mist or spray of fuel is injected into the engine cylinder. Any impurities in the fuel can block the injector nozzle's hole and lead to problems in engine operation.

The fuel injector was removed from the engine. It was disassembled and the nozzle was cleaned by immersing it in an ultrasonic washer for approximately 1 hour with some soap solution in it. This helped clean the fuel injector nozzle thoroughly. The fuel injector was assembled again and installed back on the engine following the torque specifications mentioned in the service manual. Upon cranking this time, the APU started functioning, thus proving that the nozzle hole was blocked due to debris. Figure 59 shows the APU's disassembled fuel injector. The nozzle is missing in the image as it was being cleaned.

Figure 59: Disassembled fuel injector of the APU's engine. Nozzle was immersed in an ultrasonic bath for cleaning.

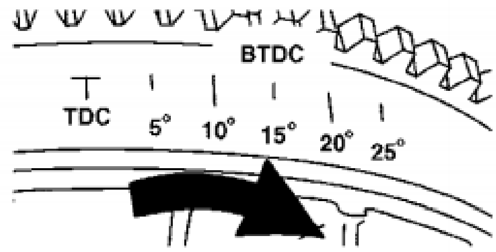
3.2. Fuel injection timing setting

After engine cranking, there was emission of white smoke and the APU’s engine was misfiring. It was left to run for 30 minutes in order to warm it up and observe if the white smoke and misfiring was due to the APU not being in operation for long.

However, even after 30 minutes of run time at 3600 rpm, the white smoke and misfiring issue still continued and hence, it was suggested that the fuel injection timing may be off. The Yanmar service manual was referred to and the fuel injection time setting procedure was followed in order to repair the generator set.

The blower fan housing cover and fan were removed until the flywheel of the engine could be accessed. The high pressure line on the end of the high pressure fuel nut was removed. This helped expose the high pressure pump’s outlet nut, from where the pressurized fuel goes to the injector.

The service manual for L70V, the diesel engine powering the APU, has a target fuel injection timing of $16^\circ \pm 0.5^\circ$ Before Top Dead Center (BTDC). Figure 60 shows the fuel injection target timing specified by Yanmar.



Fuel Injection Timing Chart

Engine	Injection Timing BTDC
L48V	17.5 ± 0.5°
L70V	16.0 ± 0.5°
L100V	15.5 ± 0.5°

Figure 60: Fuel injection target timing according to Yanmar's service manual [23]

On checking the fuel injection timing for the generator set, and from Figure 61 below, it was found that the generator's fuel pump was delivering fuel at 10° BTDC (i.e. before top dead center). This suggested that the fuel injection timing was retarded and shims had to be removed from under the fuel pump in order to achieve the target fuel injection timing.

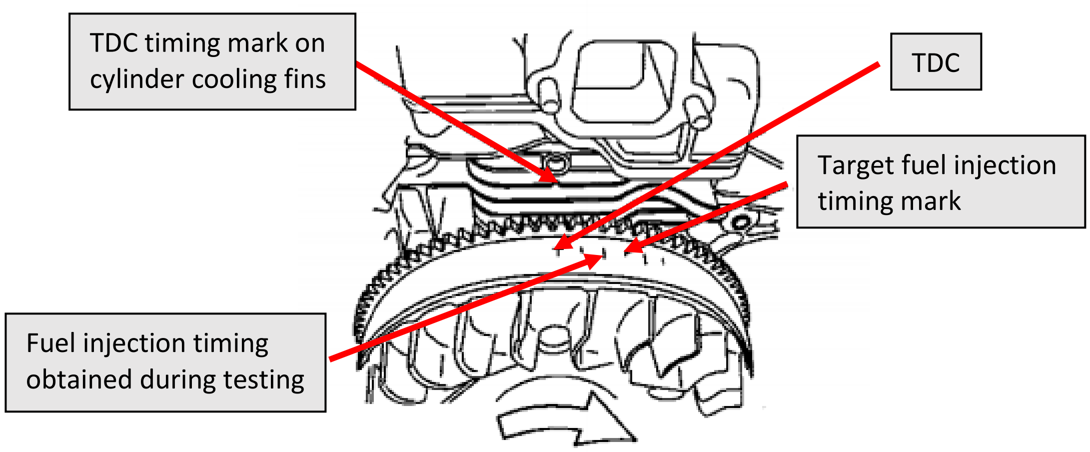


Figure 61: Labelled figure of fuel injection timing desired and timing obtained on testing [23]

Following the procedure to calculate the shim thickness to be removed, the following calculations were done:

Target fuel injection timing = 15° ± 0.5°

Fuel injection timing observed = 10°

Difference in timing = 15° - 10° = 5°

As per the service manual, 1° corresponds to 0.004 in. shim thickness [23]

Thus, the shim thickness that needs to be removed is,

$5^{\circ} \times 0.004$ in. = 0.020 in. or 0.5 mm

Following these calculations, a single shim measuring 0.02 inches was removed from under the high pressure fuel nut mounting studs and onto the crankcase mounting surface. The entire fuel system assembly was put back on the engine. On running the engine this time, the engine started and ran well, without any misfiring or white smoke emissions. This proved that the fuel injection timing was amiss and it was corrected to achieve proper operation of the generator set.

The APU was mounted in the truck's toolbox after the calibration performed above. However, once the engine was tested once it was mounted in the toolbox, it still emitted white smoke. It did not misfire this time. It was suggested that there can be oil consumption occurring and hence the smoke. However, the oil consumption and the color of the smoke did not suggest the same. On checking the fuel injection timing, this time, the fuel injection was 10° retarded.

Following the above procedure, another shim was removed from the engine and the fuel injection timing was checked. It did advance by 5°, but was still 5° retarded. There were no more shims that could be removed from the engine in order to advance the timing by 5 more degrees. It was hypothesized that due to a wear in the camshaft operation, this change in fuel injection timing could have resulted.

4. TESTING OF APU

A major part of this project dealt with the modification of the previously designed systems and fabrication of new components for the fulfilment of the project's requirements. Prior to fabrication and installation of the components, it was necessary to test the previously designed systems and determine if they could be used for this project. It was also necessary to test the modified and newly fabricated systems and components for their functionality. Chapter 4 discusses about the testing of the designs and fabrications done in Chapter 2.

4.1. APU Load and Efficiency Tests

In order to confirm if the APU would be capable of delivering specific load requirements for this project, a load test was conducted on it. The APU was rated for 3.5 KW of power generation, as seen in Table 2. Thus, a load bank was used to put a load of 1 KW on APU and observe its performance. Figure 62 shows the apparatus used to perform load test on the APU.

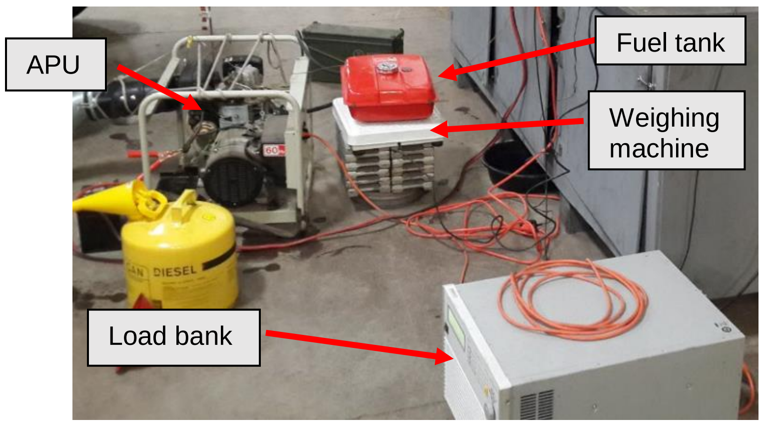


Figure 62: Apparatus to conduct the Load and Efficiency test on the APU

Along with the load testing, an efficiency test was also carried out to determine the efficiency of the APU at these loads and to determine the energy lost from the system. This efficiency of the generator set was compared with the efficiency at which the APU was to be operated, i.e. between 3.2 to 3.5 KW.

4.2. Sound (dB) test for exhaust noise

As stated in Chapter 1, one of the requirements of the project was that the NVH and exhaust noise level should be no worse than the truck's engine idling noise. Hence, after mounting the mufflers and having the generator set operational, sound tests were done on the APU system. As mentioned previously, a Mastech MS6300 Digital Multifunction Environment Meter was used to measure the sound in decibels. The 'decibels' function on the environment meter was used for the same.

4.2.1 Simulated rest stop sound measurement of APU

The Freightliner Argosy has a Caterpillar 3406 six-cylinder engine. As per the previous practices, the truck's driver had the engine on idling and satisfied his/her HVAC requirements by operating the AC/heater while the engine was idling. Hence, it was decided to compare the noise emission results from the truck's CAT 3406 engine and APU.

The sound measurements were made for the following conditions:

- Operation of Argosy's main engine
- Operation of APU without any mufflers (baseline measurements)
- Operation of APU with glass pack mufflers only
- Operation of APU with glass pack and reflective mufflers

In order to get a good estimate of the APU's noise level, it was required to run the APU at the above conditions. The Argosy was parked in between two trailers, simulating a rest stop type environment. This was done as the truck may/may not have trucks parked besides it at rest stops during its travel. Figure 63 shows the location in which the truck was parked. Figure 64 shows the 2-D top view of the points where the sound measurements were made.

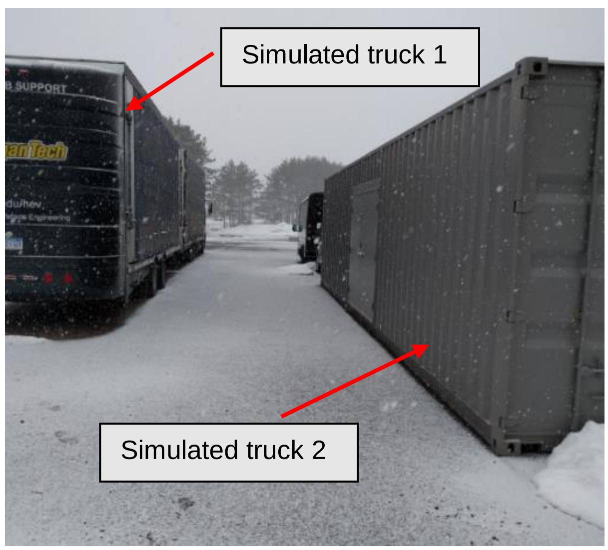


Figure 63: Simulated rest stop environment created for sound level testing of APU. The crosses signify the testing points.

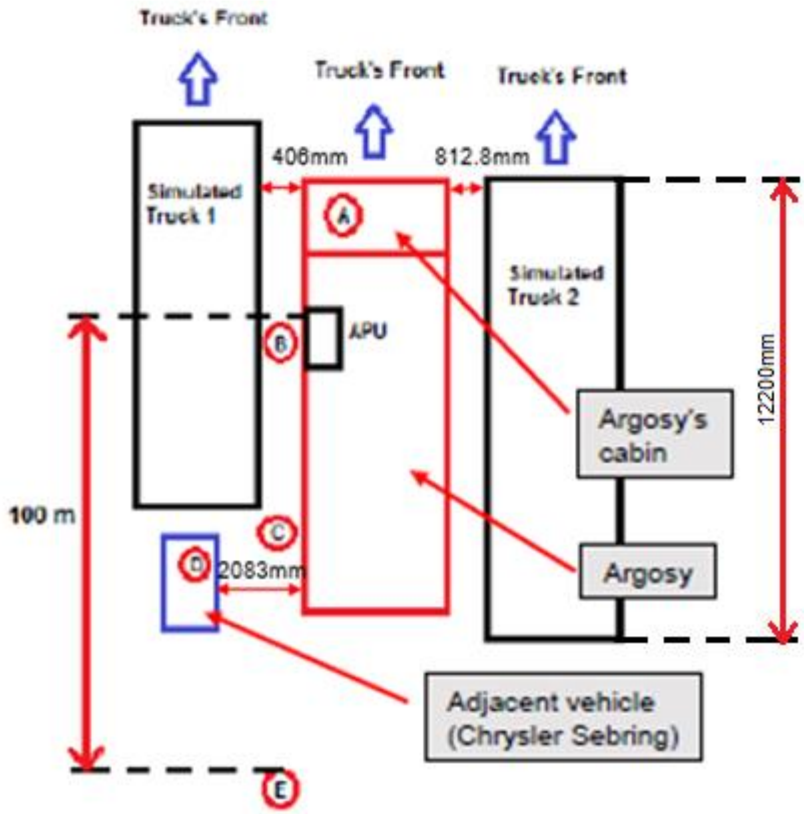


Figure 64: 2-D top view of the location of the truck in the simulated truck stop and the locations where the sound measurements were made.

From Figure 64, the noise was recorded at the following locations for different loads:

- (A) - Inside the cabin of the truck
- (B) - at a distance less than 1 m from APU
- (C) - near the mufflers of the APU exhaust system
- (D) - in the cabin of a Chrysler Sebring car (adjacent vehicle)
- (E) - at a distance of 100 m from the APU

These locations were selected for the tests so as to provide a thorough measurement of the sound emitted from the APU system. Moreover, it was necessary to record the sound that the adjacent truck's driver would anticipate. This led to the selection of locations A, B and D.

Initially, the Argosy's engine was let to idle and the truck's HVAC system was turned on. The HVAC system was operated at low, medium and high fan speeds for a total duration of 15 minutes. Sound measurements were made every 5 minutes at the locations specified above.

Next, the truck's engine was turned off and the APU was run without a muffler for 15 mins. During the APU run, a portable heater was plugged into the electrical outlet for three load conditions of low, medium and high load (requiring 600W, 900W and 1500W respectively). Sound measurements were made every 5 minutes at the locations specified above.

The APU was then made to operate with both glass pack and reflective mufflers. Again, a portable heater was plugged into the electrical outlet for three load conditions of low, medium and high load (requiring 600W, 900W and 1500W respectively). Sound measurements were made every 5 minutes at the locations specified above.

5. RESULTS

This chapter discusses the results interpreted from the testing conducted on the APU in the previous chapter.

5.1 Results for Load and Efficiency Test

Calculations were done based on the value obtained from the load and efficiency test. Also, for this project, the APU was required to run at a load between 3.2 - 3.5 KW and supply total 29 Amps to all the appliances that were to be run by it. The efficiency of the APU was extrapolated to the load required in this project by using the test observations.

Calorific Value of Diesel = 44800 KJ/kg
Density of Diesel = 0.832 kg/lit

- **For 1000 W load**

P_{set} = 1000 watts (power value set on load bank)

Fuel consumed = 0.0004414 kg/sec

Time = 600 secs

$$Energy\ from\ fuel\ =\ Fuel\ consumed\ x\ Calorific\ Value\ of\ fuel \qquad (2)$$

= 0.0004414 x 600 x 44800

= 11854.08 KJ

$$Energy\ from\ load\ =\ Power\ x\ time \qquad (3)$$

= 1 x 600

= 600 KJ

$$Efficiency\ =\ \frac{Energy\ from\ load}{Energy\ from\ fuel}\ x\ 100\ \% \qquad (4)$$

$$=\ \frac{600}{11854.08}\ \text{x 100 \%}$$

= 5.06 %

- **Test 2: Extrapolation of above results to project load requirements (3.2 KW)**

(Note: Tests were not conducted at this load. Calculations were done extrapolating the above results and using data from the Yanmar spec sheet.**)**

Power delivered by generator set = 3200 watts
Fuel consumed by generator set [7] = 1.36 liters/hour = 0.000378 kg/sec

Time = 600 secs
Calorific Value of Diesel = 44800 KJ/kg
Density of Diesel = 0.832 kg/liter

$$Energy\ from\ fuel\ =\ Fuel\ consumed\ x\ Calorific\ Value\ of\ fuel$$

= 0.000378 x 600 x 44800

= 10160.64 KJ

$$Energy\ from\ load\ =\ Power\ x\ time$$

= 3.2 x 600

= 1920 KJ

$$Efficiency\ =\ \frac{Energy\ from\ load}{Energy\ from\ fuel}\ x\ 100\ \%$$

$$=\ \frac{1920}{10160.64}\ \text{x 100 \%}$$

= 18.89 %

From the above efficiency values, it is evident that as the load increases, the APU's operational efficiency increases. At a load of 3200 Watts, we get the efficiency of approximately 19%. This is 3 times higher than the efficiency at approximately 1/3rd of the load the APU can take. This can be estimated to the fact that the generator sets are designed to operate at the maximum efficiency for a particular rpm, i.e. for maximum power production in this case. Thus, it is safe to assume that the APU will operate at its highest efficiency between loads of 3.2 - 3.5 KW.

5.2. Results of sound measurement testing

5.2.1. Truck's main engine

The sound measurements for truck's engine were taken at the locations as mentioned in Figure 64. The truck's HVAC system was operated so as to provide a load to the engine. The air conditioner (A/C) was operated at low, medium and high settings in order to provide load to the engine. Table 9 shows the results from the noise emitted when truck's CAT 3406 engine was idling.

Sr. No.	Load Type	Location (A)	Location (B)	Location (C)	Location (D)	Location (E)
1	A/C – low	64.6	81.1	72.6	42.1	69.6
2	A/C – medium	64.6	81.4	72.7	42.4	69.7
3	A/C – high	64.7	82.5	72.7	41.6	69.4

Table 7: Sound measurement observations at the test points specified previously for the truck's idling engine

5.2.2. APU operation without mufflers

The APU's engine was made to run without mufflers. This test was conducted to obtain a baseline in order to check the total sound reduction obtained by the mufflers mounted. A portable cabin heater was plugged into the APU's 120V AC outlet to provide loads of 600W, 900W and 1500W (low, medium and high settings on cabin heater) on the APU's engine.

The sound measurements for truck's engine were taken at the locations as mentioned in Figure 61. Table 10 shows the observations for the sound test for the APU without any mufflers.

Sr. No.	Load Type	Location (A)	Location (B)	Location (C)	Location (D)	Location (E)
1	Low – 600W	72.2	103.6	95	68	78.2
2	Medium – 900W	72.9	103.4	95.2	68.2	78.4
3	High – 1500W	72.8	103.8	95.4	68.5	78.5

Table 8: Measurement of sound from the APU without a muffler

From Table 10, it can be seen that the APU without a muffler has sound levels above 100 decibels. As discussed previously, OSHA states that a sound level above 85 dB can harm human ears. Thus, these values served as a baseline as to observing the sound attenuation a muffler can attain to reduce the sound level significantly.

5.2.3. Results for sound testing of APU with glass pack mufflers

As seen in Chapter 2 section 2.3.5, the glass pack mufflers were tested for sound attenuation immediately after they were mounted in the APU's exhaust system. The APU system with the glass pack mufflers emitted a sound of 100 db. This sound was very loud as compared to OSHA standards. A continuous exposure to such high sound levels could lead to adverse health effects for the driver and/or the adjacent truck drivers in the rest stop.

Due to the fact that the noise level was high, it was decided to search for a new muffler instead of carrying out the test at various test points

5.2.4. Results for sound testing of APU with glass pack and reflective mufflers

The APU was made to run with the glass pack and reflective mufflers installed in the APU's exhaust system. A portable cabin heater was plugged into the APU's 120V AC outlet to provide loads of 600W, 900W and 1500W (low, medium and high settings on cabin heater) on the APU's engine.

The sound measurements for truck's engine were taken at the locations as mentioned in Figure 61. Table 11 shows the observations for the sound test for the APU with glass pack and reflective mufflers.

Sr. No.	Load Type	Location (A)	Location (B)	Location (C)	Location (D)	Location (E)
1	Low – 600W	55.6	90.1	75.9	48	65.2
2	Medium – 900W	55.1	88.5	74.8	47.5	64.8
3	High – 1500W	54.7	88	74.4	46.6	64.5

Table 9: Sound measurements for APU with glass pack and reflective mufflers

5.2.5. Comparison between results of sound measurements for truck's idling engine, APU without muffler and APU with glass pack and reflective mufflers

Based on the observations made from the sound measurement tests conducted, graphs were plotted for noise level measured (in db.) over the locations where the sound was measured. The locations are shows in Figure 61 above. The comparisons were made for conditions of operation of the truck's idling engine, operation of APU without muffler and APU with glass pack and reflective mufflers. The values of the sound measurement were averaged for the loads applied on the truck's engine and APU engine (low, medium and high load settings) and the graphs were plotted using these averaged sound values.

Figure 65 below shows the comparison of sound level recorded for truck's idling engine, APU w/o mufflers and APU w/ mufflers for different sound measurement locations.

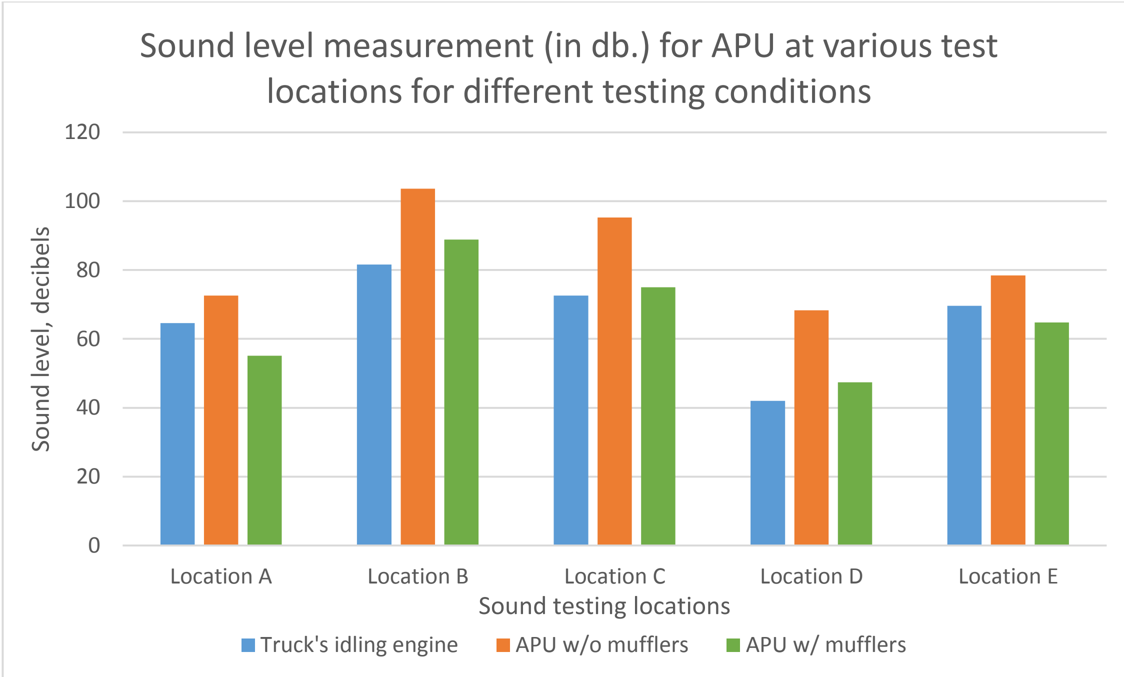


Figure 65: Plot showing the comparison of sound levels for truck's idling engine, APU w/o mufflers and APU w/ mufflers for sound measured at 5 test locations

From Figure 65, for Location A (inside the truck's cabin), the sound emitted by operation of APU is the quietest. Inside the truck's cabin, the APU with the muffler is 10 decibels quieter than the truck's engine and 17 decibels quieter than the baseline measurements. Since the driver will be resting inside the truck's cabin and the APU was the quietest, the functional requirement, of sound level being less than truck's engine idling noise, has been met for sound measurements at this location.

For Location B (at a distance less than 1 m from APU), it's evident that the sound measurements of APU without a muffler were too loud when compared to OSHA's permissible sound level of 85 decibels. However, after installation of the automotive and glass packed mufflers, considerable drop in the sound measurements has been observed. The APU without muffler is 21.9 dB louder than the truck's engine idling when measured at 1 m distance from the truck. Currently, the APU is 6 decibels louder than the truck's engine at a distance of 1 m from the truck. The functional requirement, of sound level being no greater than truck's idling engine was not achieved for this location. However, a noise reduction of 72% has been achieved from APU w/o a muffler.

For Location C (at the rear end of the truck), it can be seen that the APU w/ mufflers is only 2.4 decibels louder than the truck's idling engine. With the mufflers in the APU exhaust system, a noise reduction of 21.2% has been achieved from APU w/o mufflers. Since the sound level of APU w/ the mufflers is only 3.3% louder than the truck's idling engine, it is safe to say that the requirement of sound level being no greater than truck's idling engine was achieved for this location.

For Location D (inside the cabin of an adjacent vehicle), it can be seen that the APU's operational noise is 4 decibels higher than the truck engine's noise. Even though the values recorded for the APU's operation are louder than the values recorded for the truck's idling engine, they are still lesser than the OSHA standards of 85 decibels. Moreover, the adjacent truck's driver will have his/her truck's engine at idling and it would produce a noise of 62-65 decibels (as per the data collected previously for this project inside the cabin with the truck's engine idling). So the effective noise perceived by the adjacent driver would be negligible. Thus it can be said that the functional requirement, of sound level being less than truck's engine idling noise, has been met for sound measurements inside adjacent vehicle's cabin.

For Location E (at 100 m distance from the APU), the APU w/ mufflers is quieter than the truck's idling engine and APU w/o muffler. Thus it can be said that the functional requirement, of sound level being less than truck's engine idling noise, has been met for sound measurements made at this location.

Overall, it is safe to say that the current configuration of APU with the glass pack and reflective mufflers can be used for this system. The APU's exhaust system can definitely be improved and greater sound attenuation can be achieved.

5.3. Fuel consumption and CO_2 Emissions

One of the major reasons for mounting the APU on the truck was to reduce the truck's fuel consumption. The Argosy's 6-cylinder CAT 3406E engine consumes 0.82 gallon of diesel per hour during idling with no load on the engine [26]. It was required that this fuel consumption value of the APU be much less than the truck's to enable fuel savings.

The auxiliary fuel tank was filled up with diesel. Before starting the APU, a scale was inserted into the fuel tank and the following calculations were done to determine the volume of diesel inside the tank:

Height of fuel on the scale = 6.625"
Dimensions of the fuel tank = 12.375" x 12.875"
Volume of diesel inside the tank = 12.375 x 12.875 x 6.625
= 1051.283 in^3

Converting in^3 to gallons, we get 4.55 gallons
After testing the generator set for 1.5 hours on various loads, the fuel height was measured again so as to determine the fuel consumed.

Height of fuel on scale = 5.68"
Volume of fuel inside the fuel tank = 12.375 x 12.875 x 5.68
= 905.5 in^3
= 3.92 gallons.

Thus, fuel consumed = 4.55 – 3.92 = 0.63 gallons.

This is the fuel consumed in 1.5 hours. Thus the fuel consumed in 1 hour of APU operation is:

Fuel consumption in 1 hour = $\frac{0.63}{1.5}$

= 0.42 gallons/hr.

Thus, this proved that the fuel consumption was reduced by 50%. These values were recorded after the running the APU at no load for 30 mins. This was because the truck's fuel consumption value obtained from Han Lim's study was done at no load condition. So, in order to have an accurate comparison, APU was run at no load.

As mentioned in the introduction section, one of the major results of this project was comparing the emissions of the truck and the APU. Due to the unavailability an emissions analyzer in the APS Labs, where the truck is parked, the experimental results could not be obtained. However, it is possible to compare CO_2 values for the truck's engine at idle and APU at normal load conditions. The calculations to determine the CO_2 emission values are as follows:

Balanced stoichiometric equation for diesel fuel combustion: [27]

$$C_{12}H_{23} + 17.75(O_2 + 3.76N_2) \rightarrow 12CO_2 + 11.5H_2O + 66.74N_2 \quad (5)$$

<u>Calculations for Argosy:</u>

Fuel consumption = 0.82 gallons/hr.

Diesel in Liters = Gallons x 3.785 liters/gallon = 0.82 x 3.785 = 3.1037 liters

Also, 1 liter = 1000 cm^3

Density of Diesel = 0.832 kg/liter

$$Mass\ of\ Diesel\ (grams)\ =\ Diesel\ in\ Liters\ x\ 1000\ cm3\ x\ Density\ of\ Diesel \quad (6)$$

= 3.1037 x 1000 x 0.832
= 2582.28 grams

Now, looking at the diesel fuel combustion equation,

$$Moles\ of\ Diesel\ =\ \frac{Mass\ of\ Diesel}{(12\ x\ Mol.mass\ of\ C) + (23\ x\ Mol.mass\ of\ H)} \quad (7)$$

$$= \frac{2582.28}{(12\ x\ 12){+}(23\ x\ 1)}$$

= 15.46 moles of diesel

Now, moles of CO_2 produced per mole of diesel:

$$Moles\ of\ diesel\ x\ \frac{12\ Moles\ of\ CO2}{1\ mole\ of\ Diesel}\ =\ 15.46\ x\ 12 \quad (8)$$

= 185.52 moles of CO_2

Grams of CO_2 produced per mole of diesel:

Moles of CO_2 x $\frac{44\ grams}{1\ mole\ of\ CO2}$ = 185.52 x 44

= **8,162.88 g of CO_2 per hour**
= **2.27 g of CO_2 per second**

<u>Calculations for APU:</u>

Fuel consumption = 0.42 gallons/hr.
Diesel in Liters = Gallons x 3.785 liters/gallon = 0.42 x 3.785 = 1.5897 liters

Also, 1 liter = 1000 cm^3

Density of Diesel = 0.832 kg/liter

$$Mass\ of\ Diesel\ (grams)\ =\ Diesel\ in\ Liters\ x\ Density\ of\ Diesel$$
= 1.5897 x 0.832
= 1.322 kg
= 1322.63 grams

Now, looking at the diesel fuel combustion equation,

$$Moles\ of\ Diesel\ =\ \frac{Mass\ of\ Diesel}{(12\ x\ Mol.mass\ of\ C) + (23\ x\ Mol.mass\ of\ H)}$$
$$= \frac{1322.63}{(12\ x\ 12)+(23\ x\ 1)}$$

= 7.92 moles of diesel

Now, moles of CO_2 produced per mole of diesel:

$Moles\ of\ diesel\ x\ \frac{12\ Moles\ of\ CO2}{1\ mole\ of\ Diesel}$ = 7.92 x 12

= 95 moles of CO_2

Grams of CO_2 produced per mole of diesel:

Moles of CO_2 x $\frac{44\ grams}{1\ mole\ of\ CO2}$ = 95 x 44

= **4180 g of CO_2 per hour**
= **1.16 g of CO_2 per hour**

Based on the calculations, it can be seen that CO_2 coming out of the APU is approximately 50% lesser than the CO_2 coming out of the truck's engine. As per the information obtained from the Operations Manager of the truck, the Argosy truck idles for approximately 14 hours nine times in a year. Thus the total idling time comes out to be 126 hours in a year. Based on the calculation made above, the truck will produce 1,028 kg of CO_2 during 126 hours of idling. The APU, for the same time will produce 526 kg of CO_2. The APU's operation can reduce the CO_2 emissions from the truck, during idling, by 50%.

Moreover, as per the current cost of Diesel fuel, the driver will be spending $214.9 on fuel if the truck's engine was to be kept on idling for 126 hours. Whereas, the driver will end up spending only $110 if the APU was used instead. The APU operation thus gives the driver a 50% money saving for fuel.

6. SOLUTIONS TO FURTHER REDUCE THE APU NOISE

On a journey for a business meeting, the truck's operator came across a truck in the rest stop which had an APU installed in it. Sound level measurements were taken for that truck on the noise emitted from its APU. Figure 66 shows the locations where the truck was parked and where the sound was recorded.

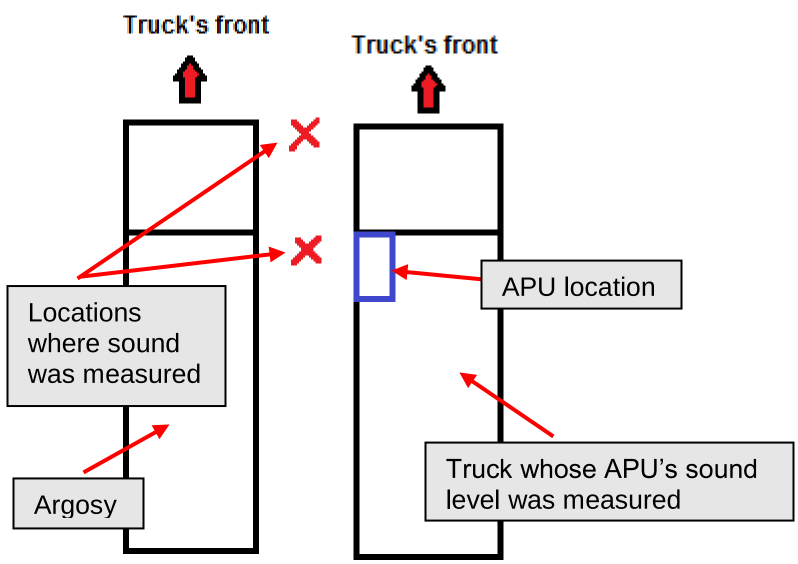


Figure 66: 2-D top view of the location the trucks were parked at and the locations where the sound was measured.

The sound measured at the above locations was approximately 70-75 decibels. It was approximately 22% quieter than the APU in this project. It was decided that a new muffler could be fabricated in order to achieve further attenuation in the current exhaust system.

6.1 Sound absorbing material

As seen from Figure 66, the fact that the sound measured at the two locations was 22% quieter for the APU in other truck when compared to the APU in this project, suggested that the noise recorded for the APU in this project was mainly the APU engine noise. Hence, there was a need for a sound absorbing material inside the APU mounting toolbox. In order to dampen the noise inside the toolbox and considering the cost and space available inside the toolbox, sound absorbing acoustic foam was the best option available. Figure 67 shows the acoustic foam sheet that can be mounted on the inner walls of the APU enclosure.

Figure 67: Sound absorbing acoustic foam sheet for noise dampening inside the APU enclosure

These foam pads are 4mm thick and can be glued to a metal surface. Depending on the level of sound absorption desired, several sheets can be mounted inside the APU enclosure, thereby increasing the thickness of the foam layer and enhancing the sound absorption. Figure 68 shows the inner surfaces available (boxed in red) for mounting the foam pads inside the APU toolbox.

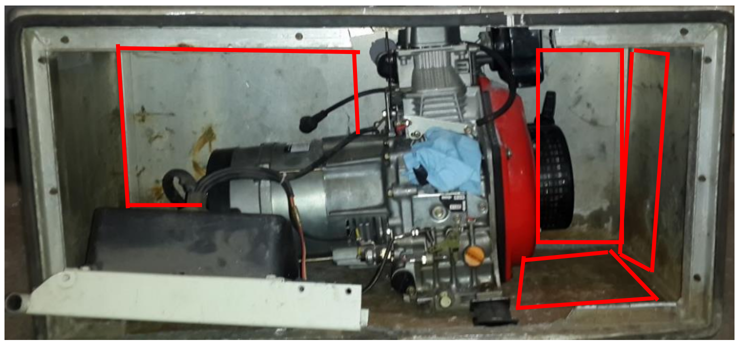


Figure 68: Inner surfaces of the toolbox available for mounting foam pads for sound absorption

6.2 Design of a new muffler

From section 2.5.2, based on the study done by Erdeem Ozdemir, it can be said that higher the muffler volume, better the sound attenuation. Also, as mentioned above, due to constraints on packaging space for high volume muffler in an automobile, manufacturers try to make the volume as small as possible and provide complex baffles in mufflers so as to produce destructive interference of sound waves.

At this stage of the project, the exhaust system already had a reflective muffler and two glass pack mufflers in series. It was also seen previously that the glass pack mufflers alone did poor muffling action for the APU system. Also, the combination of reflective and glass pack mufflers brought about a sound reduction of 15 decibels. However, this was not enough and further sound reduction was required. Having automotive, glass packed and a new muffler was also not feasible due to space constraints. Thus, in order to design a new muffler and install it in the exhaust system, it was decided that the glass packed HMW mufflers be removed and the new absorptive/glass packed muffler with a bigger volume be installed in the system. The automotive muffler was to be kept as it is in the system to attenuate the low frequency sound waves.

Two main boundary conditions were to be considered before deciding the dimensions of the new muffler. The Argosy truck can have an additional trailer attached to it through a stinger style 5th wheel coupling assembly. In order to facilitate the articulation of the additional trailer, the coupler assembly is designed to swivel side-ways. Due to this, the diameter of the new muffler had to be restricted to under 14.4”. Also, after removing the Humvee glass packed mufflers, the space available from the automotive muffler outlet till the end of the truck was approximately 114”. Thus, a muffler within these boundary dimensions was to be designed. Figure 69 below shows the 2-D front view of the space available at the rear of the truck to mount a new muffler.

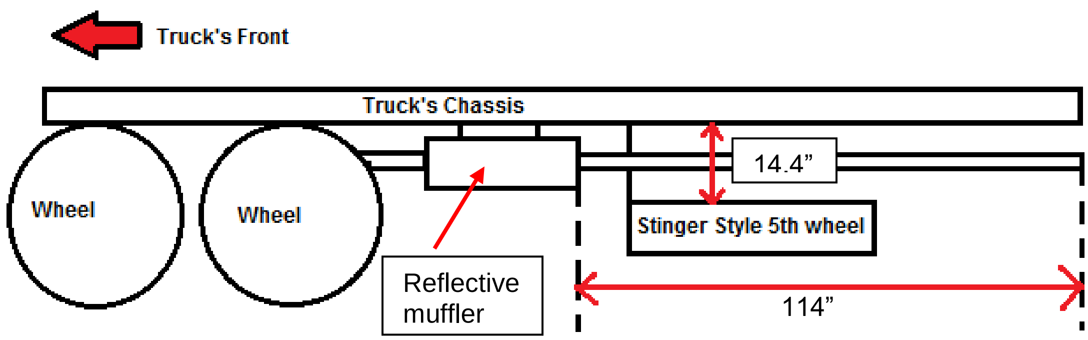


Figure 69: 2-D front view of the space available to design a new muffler

In order to determine the level of sound attenuation achieved over different diameters and length of a muffler, a MATLAB model was used. Dr. Keske and his advisor, Dr. Jason Blough, shared this model. It was written for Dr. Keske’s thesis on “Investigation of a semi-active muffler system with implementation on a snow mobile” [28]. The MATLAB code for this model has been included in the Appendix of this report.

This MATLAB model has an input screen that allows the user to feed in the values of diameter of muffler can, lengths of chambers inside the muffler, thickness of chamber walls, diameters of the opening through mufflers walls for the exhaust gases to travel to the next chamber and the exhaust gases temperature. Based on these values, the model displays a plot of sound transmission loss in dB over the frequencies of the sound waves.

It was decided to obtain the sound transmission loss for a sweep of muffler diameters and lengths. Figure 70 shows the model’s input screen.

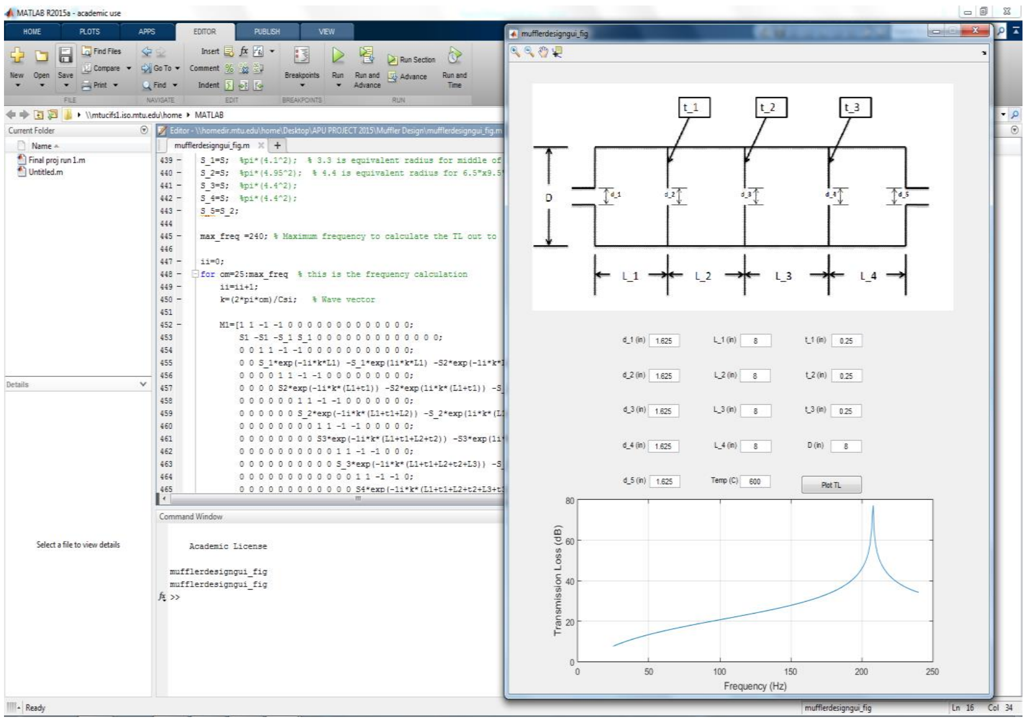


Figure 70: MATLAB model for determining the transmission loss (dB) for different diameters and lengths of muffler

As seen in Figure 71, the various geometric parameters to be varied in order to observe the performance of the muffler are as follows:

- D – Diameter of the muffler-can, (inches)
- d1, d2, d3, d4, d5 – diameter of the openings between chambers, (inches)
- L1, L2, L3, L4 – Length of chambers, (inches)
- t1, t2, t3 – thickness of the baffle plates separating the chambers, (inches)
- T – temperature of the exhaust gases, (^{0}C)

The firing frequency of the APU engine was given by:

Rotation speed of the engine = 3600 rpm

$$Firing\ frequency\ of\ the\ engine\ = \frac{Rotating\ Frequency}{2}\ Hz\ = \frac{(\frac{3600}{60})}{2} \qquad (9)$$

= 30 Hz

Upon varying the above parameters, the transmission loss (dB) for various firing frequencies is obtained. From the calculations above, since the firing frequency was 30 Hz, five harmonic multiples of 30 Hz were considered as the firing frequencies (i.e. 30, 60, 90, 120, 150 and 180). The transmission loss was calculated for the following cases:

Case 1: Constant diameter of muffler can D (12”) and variable length of muffler chamber L (from 12” till 252”) for firing frequencies of 30, 60, 90, 120, 150 and 180 Hz.

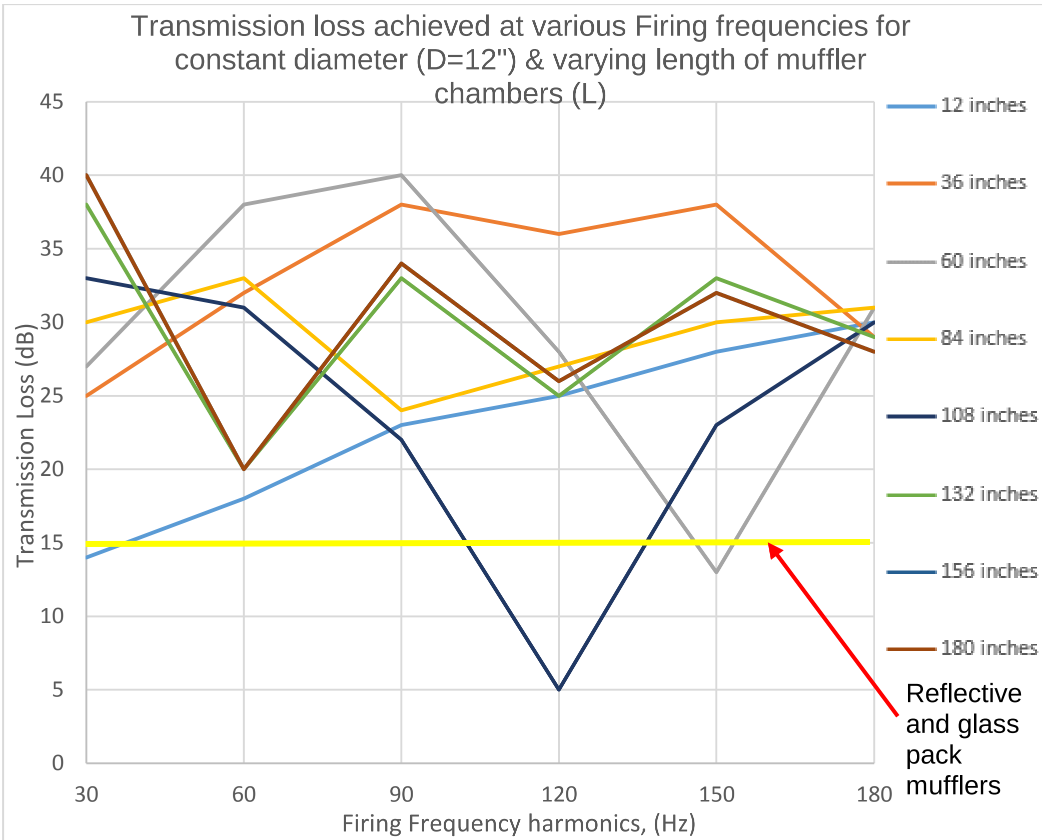


Figure 71: Plot of sound transmission loss for various engine firing frequencies for constant muffler can diameter and varying length of chamber

From Figure 71, it can be seen that the greater the length of the muffler chamber, more is the transmission loss at lower frequencies. It can also be seen that transmission loss curves for varying muffler lengths start coming close at higher frequencies. Thus, this MATLAB model is in accordance with the research done by Erdem Özdemir on effect of axial length of muffler on transmission loss.

Keeping in mind the boundary limits for sizing of the muffler discussed previously, a muffler with chamber length lesser than 114” and providing maximum transmission loss was to be selected. From Figure 71, the muffler with chamber length 36” was the best fit with 25 dB attenuation at lower frequencies and 35 dB at higher frequencies.

Now, in order to determine the diameter for which the maximum attenuation is achieved, the length was kept constant and the diameter was varied. Here, though we claimed that 36” was the best fit for the chamber length, the diameter sweep was conducted keeping in mind the maximum length available for the muffler chamber.

Case 2: Constant length of muffler chamber (96”) and variable diameter of muffler can (from 2 to 22 inches) for firing frequencies of 30, 60, 90, 120, 150 and 180 Hz.

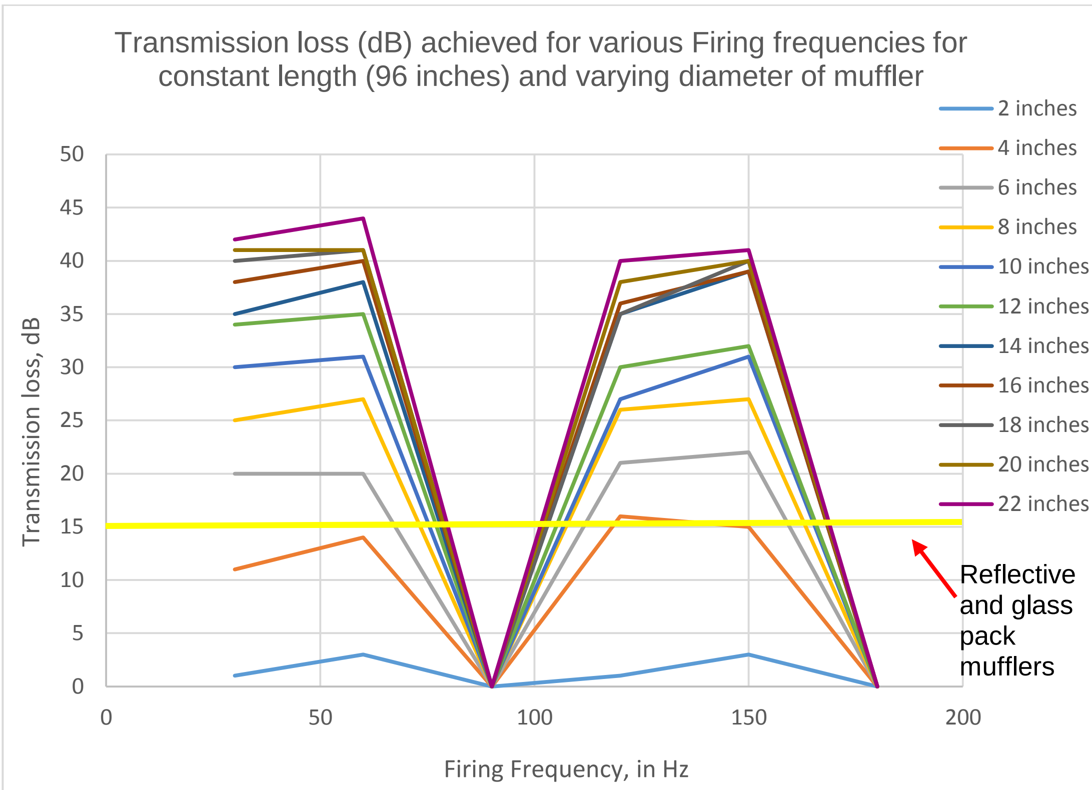


Figure 72: Plot of sound transmission loss achieved for various engine firing frequencies for constant muffler chamber length and varying muffler diameter

From Figure 72, it is visible that the increase in diameter of the muffler can is directly proportional to the increase in transmission loss. At 22 inches diameter and 8 foot chamber length, maximum transmission loss is observed at lower and higher frequencies. As mentioned previously, the current assembly of automotive and glass packed mufflers attenuated the noise by 15 decibels and further attenuation was required to make the APU operation quieter.

Keeping in mind boundary limits for the diameter of the muffler, which are D < 14.4” and L < 114”, a 12” diameter muffler was the best option available. It provided attenuation of 34 dB at lower frequencies and approximately 33 dB at higher frequencies. A 14” muffler could also be chosen in this case. However, in order to allow some clearance between the muffler surface and the coupler, it was decided that the 12” diameter muffler-can was the best option.

However, at 90 Hz and 180 Hz, no transmission loss takes place for any diameter muffler. The reason behind this can be related to the standing waves at those particular frequencies. A standing wave is a wave in a medium in which each point on the axis of the wave has an associated constant amplitude. This phenomenon can occur either because the medium is moving in the opposite direction to the wave, or it can arise in a stationary medium as a result of interference between two waves traveling in opposite directions. In the case of this project, standing waves are produced due to the latter.

speed of sound (air) in m/s is

$$c = (331.3 \times \sqrt{(1 + (\vartheta / 273.15))}) \tag{10}$$

where ϑ = temperature, in ℃

Speed of sound at 270℃ = 467.18 m/s

$$Wavelength\ (\lambda) = c / F \tag{11}$$

where F is the frequency in Hz

= 467.18/180 = 2.59 m or 8.49 foot.

As it is evident that 8 foot is the length of the exhaust pipe. Thus, it can be proved that at 180 Hz, the transmission loss will be zero due to a standing wave. Since 90 Hz is a harmonic multiple of 180 Hz, a zero transmission loss is observed at 90 Hz frequency too and at other multiples of 180 such as 90, 270, 360, etc.

Compiling the observations from Figures 71 and 72, a muffler with 36” chamber length and 12” diameter of muffler can give us a good transmission loss overall. These dimensions were decided based on the dimensional constraints and transmission losses possible. Apart from the sound waves being cancelled inside this new muffler due to its design geometrical parameters, it was decided that a sound absorbing material known as SilcoSoft would be used on the inner surface of the muffler and this would assist in sound muffling. As per a study done by Tyler W. Le Roy, 1” thickness of SilcoSoft material covering the inner surface of the muffler-can can bring about 4.5 decibels of transmission loss [29]. Figure 73 shows the 2-D schematic of the new muffler.

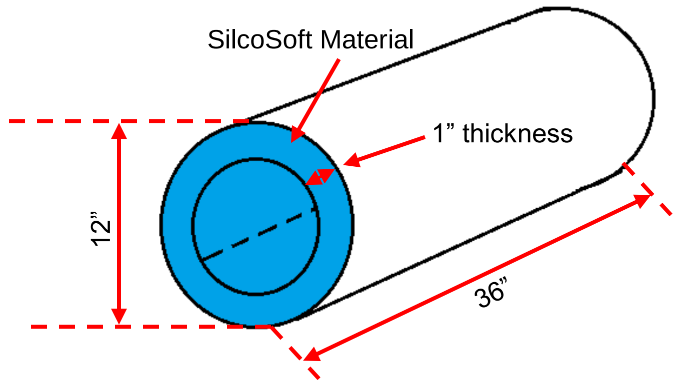


Figure 73: 2-D schematic of the new muffler with SilcoSoft material inside it

SilcoSoft is a non-woven fiber material which is used to absorb noise and vibrations. It is one of the highest temperature thermal insulator in the industry, which withstands 2000 F temperatures. Its characteristics are as follows: [30]

- Withstands temperatures up to 2000ºF (1200ºC)
- Chemical resistant
- Absorbs sound
- Softy and fleecy fiber
- Non-respirable 9-micron filament diameter
- Non-toxic
- Lightweight
- Easy handling
- Conforms to irregular surfaces

Figure 74 shows the plot of the transmission loss achieved in the current exhaust system and the transmission loss that can be achieved by installing the above designed muffler. These transmission losses are with respect to the APU operation w/o a muffler producing 103.8 decibels of sound.

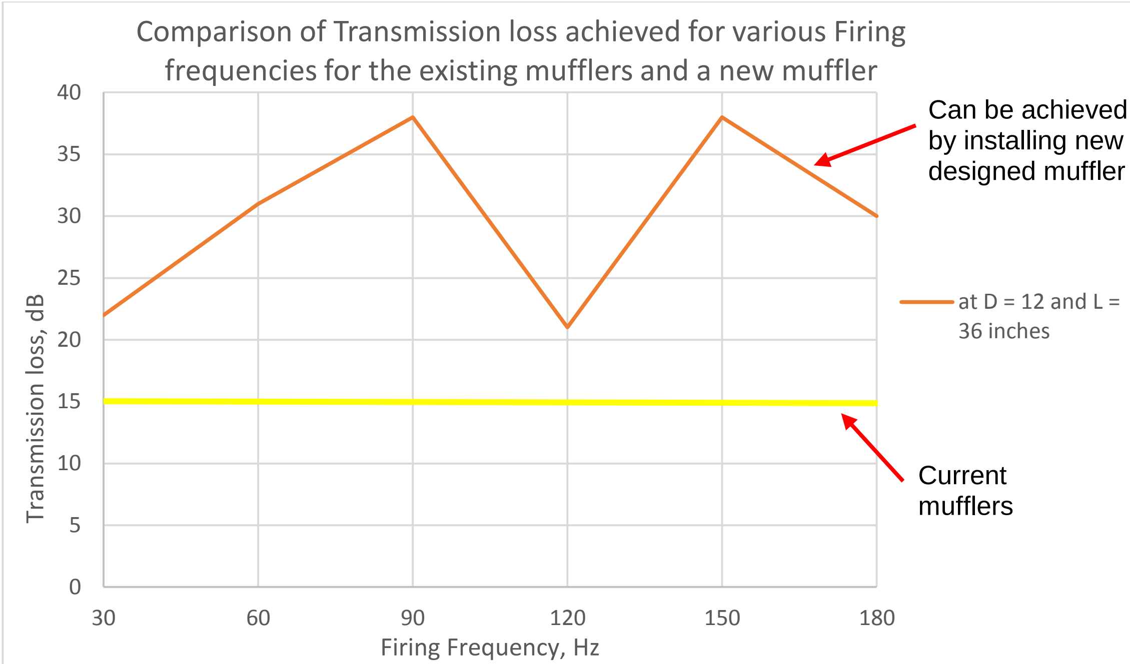


Figure 74: Sound transmission loss achieved from current mufflers installed in the system and the new designed muffler that can be installed in the system

As seen from Figure 74, a new muffler with dimensions of 36” length, 12” diameter and 1” thickness layer of SilcoSoft insulation can bring about a sound transmission loss twice the transmission loss obtained from the current mufflers.

CONCLUSION

This project was aimed at reducing the idling, fuel consumption and emissions from the Argosy truck. Apart from these, several functional requirements were listed for this project. Each requirement was fulfilled.

The APU was very easy to use with the driver just having to crank it with a key inside the truck's cabin. A primer was installed too to aid the driver in starting the APU. The NVH and exhaust noise of the APU was lesser than the truck's idling engine inside the truck's cabin, inside adjacent truck's cabin and at a distance of 100 m from the truck. Moreover, it also lies within the OSHA sound limits of 85 dB, making it possible for the driver to keep it running the entire night. The APU and all its accessories were mounted in such a way that the truck's operation was not affected. Electrical connections were provided inside the truck's cabin and outside the APU's mounting box to allow usage of portable heater/cooler inside the truck's cabin and charge the truck's batteries and operate the block heater mounted on the truck's chassis respectively. All electrical and fuel system connections were secured and safe.

Tests were conducted on the APU and comparisons were drawn with the truck's idling engine so as to prove why the APU was better. In order to achieve silent operation of the APU, analysis on mufflers was done and an automotive muffler along with two glass packed mufflers reduced the noise during APU's operation by approximately 14 dB when outside the truck and 17 dB when inside the truck's cabin.

From all the design, fabrication and testing conducted on this project, it can be seen that the APU is a nice way to reduce the truck's idling and carry out other activities like charging the truck's batteries and powering other 12V and 120V AC accessories inside the truck's cabin. By using this device, the fuel consumption reduces by 50%, the CO_2 emitted reduced by approximately 51% and a 49% savings in money for fuel could be achieved. These are significant values and can help save the environment from pollution and save the driver's money going into buying fuel.

Table 12 shows the summary of the requirements and results for this project.

Sr. No.	Functional Requirement	Results
1	Ease of Use	APU can be started/switched-off from inside the truck's cabin, APU starts immediately on cranking (additional primer provided for troubleshooting), electrical outlet have been ergonomically placed as per driver's convenience.
2	NVH and exhaust odor not worse than production engine's noise level	Rubber dampers mounted between APU and APU enclosure for damping vibrations, mufflers installed and tested for APU system – current mufflers allow driver to rest in cabin and do not pose any high noise levels for adjacent vehicle's drivers.
3	Truck's operation not to be affected	All features of the truck are operable with the APU turned off.
4	Operation of portable HVAC system, charging of truck's batteries and operation of truck's block heaters	A 120 V AC portable cabin heater/cooler can be operated using the 120V AC outlet installed in the truck's cabin, the truck's batteries and block heater can be operated using the 120 V AC outlets installed on the APU's mounting box. All connections were tested and the devices ran successfully.
5	Safety of System	The entire APU system is safe to use. The wires chosen for electrical connections are as per the standard AWG sizes, outlets are as per the voltage ratings and current drawn through them, the fuel system connections are proper and proper ventilation has been provided inside the APU enclosure to prevent any adverse effects due to heat generated from APU's engine operation.

Table 10: A summary of the project's functional requirements and the results obtained for each requirement

RECOMMENDATIONS FOR FUTURE WORK

Below are a few recommendations to expand this project towards its efficient working:

- **Fuel injection timing setting:**

  It was observed that the fuel injection timing was 5° retarded than the ideal target timing. Due to this, white smoke emissions could be seen due to improper combustion. The fuel injection was already advanced by 5° by removing a shim from under the fuel pump. Currently, there are no more shims to remove so as to advance the fuel injection timing. The compression of the spring on the mechanical fuel pressure pump in the engine can be varied to get advanced timing and good output.

  It cannot be determined presently if the fuel injection timing is responsible for the noise coming out from the engine. Even though we consider that the timing is responsible for the noise, we need to quantify the claims. Further tests can be conducted on the engine and by measuring the cylinder pressures, we can conclude if retarded fuel injection is an advantage or disadvantage.

- **Absorptive Foam Application:**

  A layer of absorptive foam can be mounted on the inner surface of the toolbox which holds the APU. This is required to dampen the noise produced due to engine operation.

- **New Muffler Fabrication:**

  Fabrication and installation of the new muffler designed in the previous section.

- **High temperature Shut-off:**

  Currently, there is no sensor or device to shut off the APU in case high temperatures are achieved inside the APU enclosure. Yanmar states that the operating temperature limits for the APU should be no more than 80℃. Thus, a high temperature shut down mechanism can be designed and installed to protect the APU from any damage.

- **Mechanical shut-off lever reset:**

  When the APU is switched-off using the key switch inside the cabin, a mechanical lever gets shifted to the OFF position. Figure 75 shows the mechanical shut-off lever installed on the APU.

Figure 75: Mechanical shut-off lever on the APU

In order to start the APU again, the driver has to manually shift the mechanical lever to the ‘RUN’ position (i.e. to the right side). A solenoid operated plunger can be installed on the APU to automatically push the lever to the RUN position when the driver wants to switch on the APU from inside the cabin.

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APPENDIX

Coding for MATLAB model used to determine the dimensions for a new muffler for noise attenuation.

```
function varargout = mufflerdesigngui_fig(varargin)
% MUFFLERDESIGNGUI_FIG M-file for mufflerdesigngui_fig.fig
%      MUFFLERDESIGNGUI_FIG, by itself, creates a new MUFFLERDESIGNGUI_FIG or raises the
existing
%      singleton*.
%
%      H = MUFFLERDESIGNGUI_FIG returns the handle to a new MUFFLERDESIGNGUI_FIG or the
handle to
%      the existing singleton*.
%
%      MUFFLERDESIGNGUI_FIG('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in MUFFLERDESIGNGUI_FIG.M with the given input arguments.
%
%      MUFFLERDESIGNGUI_FIG('Property','Value',...) creates a new MUFFLERDESIGNGUI_FIG or
raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before mufflerdesigngui_fig_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to mufflerdesigngui_fig_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help mufflerdesigngui_fig

% Last Modified by GUIDE v2.5 17-Apr-2009 17:07:43

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @mufflerdesigngui_fig_OpeningFcn, ...
                   'gui_OutputFcn',  @mufflerdesigngui_fig_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
```

```
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before mufflerdesigngui_fig is made visible.
function mufflerdesigngui_fig_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to mufflerdesigngui_fig (see VARARGIN)

% Choose default command line output for mufflerdesigngui_fig
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes mufflerdesigngui_fig wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = mufflerdesigngui_fig_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;



function D_Callback(hObject, eventdata, handles)
% hObject    handle to D (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of D as text
%        str2double(get(hObject,'String')) returns contents of D as a double


% --- Executes during object creation, after setting all properties.
function D_CreateFcn(hObject, eventdata, handles)
% hObject    handle to D (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
```

```
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function d_1_Callback(hObject, eventdata, handles)
% hObject    handle to d_1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of d_1 as text
%        str2double(get(hObject,'String')) returns contents of d_1 as a double


% --- Executes during object creation, after setting all properties.
function d_1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to d_1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function d_2_Callback(hObject, eventdata, handles)
% hObject    handle to d_2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of d_2 as text
%        str2double(get(hObject,'String')) returns contents of d_2 as a double


% --- Executes during object creation, after setting all properties.
function d_2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to d_2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
```

```
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function d_3_Callback(hObject, eventdata, handles)
% hObject    handle to d_3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of d_3 as text
%        str2double(get(hObject,'String')) returns contents of d_3 as a double


% --- Executes during object creation, after setting all properties.
function d_3_CreateFcn(hObject, eventdata, handles)
% hObject    handle to d_3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function d_4_Callback(hObject, eventdata, handles)
% hObject    handle to d_4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of d_4 as text
%        str2double(get(hObject,'String')) returns contents of d_4 as a double


% --- Executes during object creation, after setting all properties.
function d_4_CreateFcn(hObject, eventdata, handles)
% hObject    handle to d_4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
```

```
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function d_5_Callback(hObject, eventdata, handles)
% hObject    handle to d_5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of d_5 as text
%        str2double(get(hObject,'String')) returns contents of d_5 as a double


% --- Executes during object creation, after setting all properties.
function d_5_CreateFcn(hObject, eventdata, handles)
% hObject    handle to d_5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


function L_1_Callback(hObject, eventdata, handles)
% hObject    handle to L_1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of L_1 as text
%        str2double(get(hObject,'String')) returns contents of L_1 as a double


% --- Executes during object creation, after setting all properties.
function L_1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to L_1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
function L_2_Callback(hObject, eventdata, handles)
% hObject    handle to L_2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of L_2 as text
%        str2double(get(hObject,'String')) returns contents of L_2 as a double


% --- Executes during object creation, after setting all properties.
function L_2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to L_2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function L_3_Callback(hObject, eventdata, handles)
% hObject    handle to L_3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of L_3 as text
%        str2double(get(hObject,'String')) returns contents of L_3 as a double


% --- Executes during object creation, after setting all properties.
function L_3_CreateFcn(hObject, eventdata, handles)
% hObject    handle to L_3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function L_4_Callback(hObject, eventdata, handles)
```

```
% hObject    handle to L_4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of L_4 as text
%        str2double(get(hObject,'String')) returns contents of L_4 as a double


% --- Executes during object creation, after setting all properties.
function L_4_CreateFcn(hObject, eventdata, handles)
% hObject    handle to L_4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function t_1_Callback(hObject, eventdata, handles)
% hObject    handle to t_1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of t_1 as text
%        str2double(get(hObject,'String')) returns contents of t_1 as a double


% --- Executes during object creation, after setting all properties.
function t_1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to t_1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function t_2_Callback(hObject, eventdata, handles)
% hObject    handle to t_2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
```

```
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of t_2 as text
%        str2double(get(hObject,'String')) returns contents of t_2 as a double


% --- Executes during object creation, after setting all properties.
function t_2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to t_2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function t_3_Callback(hObject, eventdata, handles)
% hObject    handle to t_3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of t_3 as text
%        str2double(get(hObject,'String')) returns contents of t_3 as a double


% --- Executes during object creation, after setting all properties.
function t_3_CreateFcn(hObject, eventdata, handles)
% hObject    handle to t_3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in plotTL.
function plotTL_Callback(hObject, eventdata, handles)
% hObject    handle to plotTL (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
D = str2num(get(handles.D,'String'))./12;
d_1 = str2num(get(handles.d_1,'String'))./12;
d_2 = str2num(get(handles.d_2,'String'))./12;
d_3 = str2num(get(handles.d_3,'String'))./12;
d_4 = str2num(get(handles.d_4,'String'))./12;
d_5 = str2num(get(handles.d_5,'String'))./12;
L_1 = str2num(get(handles.L_1,'String'))./12;
L_2 = str2num(get(handles.L_2,'String'))./12;
L_3 = str2num(get(handles.L_3,'String'))./12;
L_4 = str2num(get(handles.L_4,'String'))./12;
t_1 = str2num(get(handles.t_1,'String'))./12;
t_2 = str2num(get(handles.t_2,'String'))./12;
t_3 = str2num(get(handles.t_3,'String'))./12;
T_C = str2num(get(handles.T,'String'));

Tc=T_C;                % Exhaust Temperature in degrees C
Cm=331.4+0.6*Tc;       % Speed of sound - m/s (Assuming constant Temp)
Csi=Cm*3.2808;         % Speed of sound - ft/s
L1 = L_1;
L2 = L_2;
L3 = L_3;
L4 = L_4;
t1 = t_1;
t2 = t_2;
t3 = t_3;
S1=pi*(d_1/2)^2;
S2=pi*(d_2/2)^2;
S3=pi*(d_3/2)^2;
S4=pi*(d_4/2)^2;
S5=pi*(d_5/2)^2;
S=pi*(D/2)^2;

%ii=0;
%for om=25:2500
%    ii=ii+1;
%    k=(2*pi*om)/Csi;   % Wave vector

%     M1=[1 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
%         S1 -S1 -S S 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
%         0 0 1 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0;
%         0 0 S*exp(-j*k*L1) -S*exp(j*k*L1) -S2*exp(-j*k*L1) S2*exp(j*k*L1) 0 0 0 0 0 0 0
0 0 0 0;
%         0 0 0 0 1 1 -1 -1 0 0 0 0 0 0 0 0 0 0;
%         0 0 0 0 S2*exp(-j*k*(L1+t1)) -S2*exp(j*k*(L1+t1)) -S*exp(-j*k*(L1+t1))
S*exp(j*k*(L1+t1)) 0 0 0 0 0 0 0 0 0 0;
%         0 0 0 0 0 0 1 1 -1 -1 0 0 0 0 0 0 0 0;
%         0 0 0 0 0 0 S*exp(-j*k*(L1+t1+L2)) -S*exp(j*k*(L1+t1+L2)) -S3*exp(-
j*k*(L1+t1+L2)) S3*exp(j*k*(L1+t1+L2)) 0 0 0 0 0 0 0 0;
%         0 0 0 0 0 0 0 0 1 1 -1 -1 0 0 0 0 0 0;
%         0 0 0 0 0 0 0 0 S3*exp(-j*k*(L1+t1+L2+t2)) -S3*exp(j*k*(L1+t1+L2+t2)) -S*exp(-
```

```
j*k*(L1+t1+L2+t2)) S*exp(j*k*(L1+t1+L2+t2)) 0 0 0 0 0;
%         0 0 0 0 0 0 0 0 0 0 0 1 1 -1 -1 0 0 0;
%         0 0 0 0 0 0 0 0 0 0 0 S*exp(-j*k*(L1+t1+L2+t2+L3)) -S*exp(j*k*(L1+t1+L2+t2+L3)) -
S4*exp(-j*k*(L1+t1+L2+t2+L3)) S4*exp(j*k*(L1+t1+L2+t2+L3)) 0 0 0;
%         0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 -1 -1 0;
%         0 0 0 0 0 0 0 0 0 0 0 0 0 S4*exp(-j*k*(L1+t1+L2+t2+L3+t3)) -
S4*exp(j*k*(L1+t1+L2+t2+L3+t3)) -S*exp(-j*k*(L1+t1+L2+t2+L3+t3))
S*exp(j*k*(L1+t1+L2+t2+L3+t3)) 0;
%         0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 -1;
%         0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 S*exp(-j*k*(L1+t1+L2+t2+L3+t3+L4)) -
S*exp(j*k*(L1+t1+L2+t2+L3+t3+L4)) -S5*exp(-j*k*(L1+t1+L2+t2+L3+t3+L4));
%         1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];


%    M2=[0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;1];



    % Set radiuses/areas of the expansion chambers
S=pi*(D/2)^2;  % Lines below can be changed for different radiuses for each section
S_1=S;  %pi*(4.1^2);  % 3.3 is equivalent radius for middle of top of box which looks
like a wedge, based on volume
S_2=S;  %pi*(4.95^2);  % 4.4 is equivalent radius for 6.5"x9.5" bottom part of box
S_3=S;  %pi*(4.4^2);
S_4=S;  %pi*(4.4^2);
S_5=S_2;

max_freq =250; % Maximum frequency to calculate the TL out to

ii=0;
for om=25:max_freq  % this is the frequency calculation
    ii=ii+1;
    k=(2*pi*om)/Csi;   % Wave vector

    M1=[1 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
        S1 -S1 -S_1 S_1 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
        0 0 1 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0;
        0 0 S_1*exp(-1i*k*L1) -S_1*exp(1i*k*L1) -S2*exp(-1i*k*L1) S2*exp(1i*k*L1) 0 0 0 0
0 0 0 0 0 0 0 0;
        0 0 0 0 1 1 -1 -1 0 0 0 0 0 0 0 0 0 0;
        0 0 0 0 S2*exp(-1i*k*(L1+t1)) -S2*exp(1i*k*(L1+t1)) -S_2*exp(-1i*k*(L1+t1))
S_2*exp(1i*k*(L1+t1)) 0 0 0 0 0 0 0 0 0 0;
        0 0 0 0 0 0 1 1 -1 -1 0 0 0 0 0 0 0 0;
        0 0 0 0 0 0 S_2*exp(-1i*k*(L1+t1+L2)) -S_2*exp(1i*k*(L1+t1+L2)) -S3*exp(-
1i*k*(L1+t1+L2)) S3*exp(1i*k*(L1+t1+L2)) 0 0 0 0 0 0 0 0;
        0 0 0 0 0 0 0 0 1 1 -1 -1 0 0 0 0 0 0;
        0 0 0 0 0 0 0 0 S3*exp(-1i*k*(L1+t1+L2+t2)) -S3*exp(1i*k*(L1+t1+L2+t2)) -
S_3*exp(-1i*k*(L1+t1+L2+t2)) S_3*exp(1i*k*(L1+t1+L2+t2)) 0 0 0 0 0 0;
        0 0 0 0 0 0 0 0 0 0 1 1 -1 -1 0 0 0 0;
        0 0 0 0 0 0 0 0 0 0 S_3*exp(-1i*k*(L1+t1+L2+t2+L3)) -
S_3*exp(1i*k*(L1+t1+L2+t2+L3)) -S4*exp(-1i*k*(L1+t1+L2+t2+L3))
```

```
S4*exp(1i*k*(L1+t1+L2+t2+L3)) 0 0 0;
        0 0 0 0 0 0 0 0 0 0 0 0 1 1 -1 -1 0;
        0 0 0 0 0 0 0 0 0 0 0 0 S4*exp(-1i*k*(L1+t1+L2+t2+L3+t3)) -
S4*exp(1i*k*(L1+t1+L2+t2+L3+t3)) -S_4*exp(-1i*k*(L1+t1+L2+t2+L3+t3))
S_4*exp(1i*k*(L1+t1+L2+t2+L3+t3)) 0;
        0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 -1;
        0 0 0 0 0 0 0 0 0 0 0 0 0 0 S_4*exp(-1i*k*(L1+t1+L2+t2+L3+t3+L4)) -
S_4*exp(1i*k*(L1+t1+L2+t2+L3+t3+L4)) -S5*exp(-1i*k*(L1+t1+L2+t2+L3+t3+L4));
        1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];

    M2=[0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;1];



    Chamber2=M1\M2;

    A1(ii)=abs(Chamber2(1,1));
    B1(ii)=abs(Chamber2(2,1));
    A2(ii)=abs(Chamber2(3,1));
    B2(ii)=abs(Chamber2(4,1));
    A3(ii)=abs(Chamber2(5,1));
    B3(ii)=abs(Chamber2(6,1));
    A4(ii)=abs(Chamber2(7,1));
    B4(ii)=abs(Chamber2(8,1));
    A5(ii)=abs(Chamber2(9,1));
    B5(ii)=abs(Chamber2(10,1));
    A6(ii)=abs(Chamber2(11,1));
    B6(ii)=abs(Chamber2(12,1));
    A7(ii)=abs(Chamber2(13,1));
    B7(ii)=abs(Chamber2(14,1));
    A8(ii)=abs(Chamber2(15,1));
    B8(ii)=abs(Chamber2(16,1));
    A9(ii)=abs(Chamber2(17,1));

    om=[25:max_freq];
    TL(ii)=10*log10((A1(ii)/A9(ii))^2);
end

axes(handles.axes1);
plot(om,TL); grid on
xlabel('Frequency (Hz)')
ylabel('Transmission Loss (dB)')
% PLot lines for frequencies to avoid
% Set rpm which engine will run at
% hold on;
% rpm = 11000;
% freq_avoid = [1:7]*rpm/60;
% plot_freq = reshape([freq_avoid ; freq_avoid],2*length(freq_avoid),1);
% plot(plot_freq,[min(TL) max(TL) max(TL) min(TL) min(TL) max(TL) max(TL) min(TL) min(TL)
max(TL) max(TL) min(TL) min(TL) max(TL)])
```

```
% hold off

axes(handles.axes2);
[data,map]=imread('muffler.gif');
pic=ind2rgb(data,map);
image(pic);
axis off




function T_Callback(hObject, eventdata, handles)
% hObject    handle to T (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of T as text
%        str2double(get(hObject,'String')) returns contents of T as a double


% --- Executes during object creation, after setting all properties.
function T_CreateFcn(hObject, eventdata, handles)
% hObject    handle to T (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

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