Analysis of Air Conditioning Compressor Mount to Reduce Noise, Vibration and Harshness

Team #5: FFNS

Project Advisor: Mal Symonds

Sponsored by: New Flyer Industries

Final Design Report

Due December 5, 2011

Prepared for: Paul Labossiere

Department of Mechanical Engineering

University of Manitoba

Jasen Fullante

Matt Fair

Dave Newton

Justin Strahl

December 5, 2011

Dr. Paul Labossiere
Department of Mechanical Engineering
Faculty of Engineering
University of Manitoba
Winnipeg, Manitoba
R3T 2N2

Dear Professor Labossiere,

Please find attached the final written report entitled "Analysis of Air Conditioning Compressor Mount to Reduce Noise, Vibration and Harshness." This report has been submitted on December 5, 2011 by Team 5. Team 5 consists of Matt Fair, Jasen Fullante, Dave Newton, and Justin Strahl.

Our report will discuss a possible design solution for the excess vibration and noise created by the air conditioning compressor during the operation of the bus. The content of this report contains a possible design solution for the problem of vibration created by the air conditioning compressor as well as a possible solution for the issue of belt whip that is present on the drive belt that powers the compressor. Also included in the report are possible future solutions to these problems that would be better used on buses that have not already been assembled. There are also future solutions that are not yet feasible as they are not outfitted to this type of situation. If you have any questions regarding this report please feel free to contact any one of us through the following email addresses:

Sincerely,

Team # 5: FFNS,

Matt Fair - umfair2@cc.umanitoba.ca

____

Jasen Fullante - umfullaj@cc.umanitoba.ca

____

Justin Strahl - umstrahl@umanitoba.ca

____

Dave Newton – umnewtod@umanitoba.ca

____

Abstract

The purpose of this report is to design a solution originating in New Flyer Industries' Xcelsior bus line. The issue is excessive vibration and noise generated in the engine compartment caused by the air conditioning compressor. Additionally, belt whip between the air conditioning compressor and the engine crankshaft pulley is to be reduced. This report will also examine future considerations for design solutions including methods of electronic damping, an alternative air conditioning compressor, and air conditioning hoses.

It is determined that a ROSTA ISOCOL U 50 vibration mounting plate is recommended to reduce noise and vibration caused by the operating compressor. A torsional damping pulley is suggested to be installed in place of the crankshaft pulley in order to reduce belt whip during operation. For future considerations, a modular damping unit integrated with a screw compressor and Galaxy 4890 hoses is recommended.

Table of Contents

List of Figures

List of Tables

1. Introduction

The purpose of this report is to recommend a final design based on our customer's needs. This report will first outline the customer's field of operation and how our design project coincides with it. Next, it will outline the customer needs, specifications, and our project objectives. After these points have been outlined, details of the final design including components, assembly and a brief cost analysis will be discussed. Finally, future design considerations and a final recommendation will be made.

1.1. New Flyer Industries Background

New Flyer Industries (**NFI**) is one of the leading bus manufacturers in North America, and is one of the top suppliers to many different cities across the continent. NFI was founded in 1930 as Western Auto and Truck Body Ltd. After several breakthroughs in the coach industry, such as the placement of the engine in the coach body to provide more seating, New Flyer Industries Ltd, simply Flyer industries at the time (1971), became a predominant bus line manufacturer. When the company was acquired by a Holland bus manufacturer in 1986, the name of the company was finally changed to New Flyer Industries Ltd [1].

The heating and cooling department of NFI's design team issued this project. This team deals solely with heating, ventilation and air conditioning (**HVAC**) on all bus lines. It is their responsibility to solve to any problems that may arise in the HVAC system of the bus. The main goals of this project report are to reduce the noise and vibration that is produced by the air conditioning compressor (**ACC)** and to reduce the belt whip that is experienced by the drive belt of the ACC.

1.2. Customer Needs

NFI requires a reduction in the noise vibration and harshness (**NVH**) created by the ACC. Furthermore, New Flyer Industries requires a reduction in the belt whip. The belt is currently connected between the ACC and the engine crankshaft pulley. The crankshaft pulley of the engine provides power to the ACC through the driven belt. Under the initial design considerations and meetings with NFI, it was assumed that the two issues of NVH and belt whip were linked and could be solved together. However, after further investigation and meetings with NFI, it appears these two problems need to be dealt with independently.

When standing inside the bus, there is a noticeable difference in noise level when the ACC comes into operation. There is vibration felt through the floor and seats in the rear of the bus and audible noise as a result of the created vibration. However, when observing the rear compartment from outside of the bus with the engine of the bus running and operating the ACC, there is not a noticeable difference in noise or vibration. This shows the problem effects the passengers who will ride the bus in the future, and therefore effects the bus's owners and operators. Due to this noise and vibration, some of NFI's customers are refusing to pay for their orders of buses until this problem is fixed. Therefore, there is a need to reduce this NVH to a suitable level for NFI's clients so their contracts and payments can be completed.

A secondary problem with the operation of the ACC system involves the belt powering the ACC from the engine. When observing the belt that drives the ACC, there is belt whip of approximately 2-3 inches from top to bottom in amplitude. Excessive belt whip causes wear on the operating belt and can lead to belt failure. The customer desires no belt whip. However, NFI has created various options to reduce belt whip by approximately 90%, and therefore, the reduction of belt whip is the secondary need.

1.3. Target Specifications

New Flyer Industries has set two main target specifications as goals for the design. The primary goal is the reduction of NVH created by the ACC, and the other is the reduction of belt whip and subsequent increase in belt life. NFI has set a design goal of a reduction in noise by 2-4 dB. There is currently no quantified value for noise being produced by the vibration of the ACC and the 2-4 dB reduction is put forth by NFI. Therefore, a general solution will be given and a quantifiable reduction of NVH is not possible.

NFI's target specification for belt operation is to increase belt life to 50 000 miles run time. This target is also based on NFI's customer's needs. A value of run time increase is not measurable as there is currently no standard given by NFI.

There is also a need to maintain ease of access to the currently operating system. This ensures ease of maintenance and changing of any belts or compressors as they are located at the front of the engine compartment. The following figure shows the connection of the ACC to the belt and the hoses.

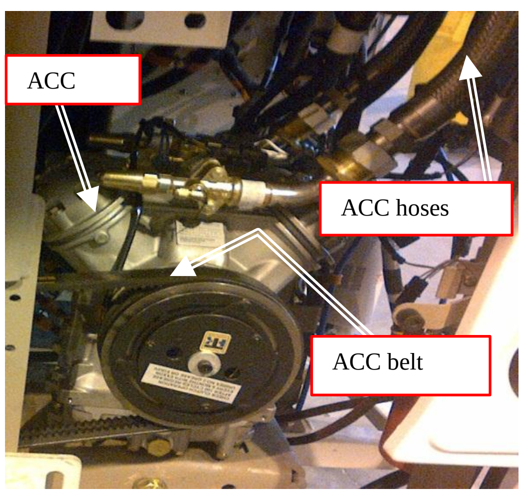


Figure 1: ACC layout and connections

1.4. Project Objectives

The primary project objective is to provide a design solution and detailed report to reduce the NVH created by the ACC. Secondary objectives are to increase belt life while reducing belt whip and maintaining ease of maintenance. The belt and connecting components must continue to be easily accessible in the rear compartment of the bus. Preliminary costs will be considered in the report.

2. Design Change Considerations

On Nov. 8, 2011 Team FFNS met with respective clients at NFI to discuss the concepts created, along with the scoring and screening associated with the Concept Development Report. Upon discussion of all of the concepts, it was determined NFI had previously attempted to implement each one of them into the current Xcelsior bus line. However, each concept failed to solve both the issues of NVH and belt whip. Further details about constraints and potential designs were discussed and it was decided that a new constraint needed to be taken into account.

The new design issue put forward by NFI was hose life. Originally, the design focused on reducing belt whip and NVH associated with the current layout of the Xcelsior bus line. However, NFI has determined hose life as a new prominent issue. The type of hoses was initially constrained as the ACC had to be rigidly mounted. If the ACC is not rigidly mounted, the hoses may fail during operation. As a result, the idea of implementing new hoses has become a design issue. A new approach to the problem was suggested. Since the solution now requires a balance between three variables a new approach was implemented. Figure 2 depicts the new approach to the given problem.

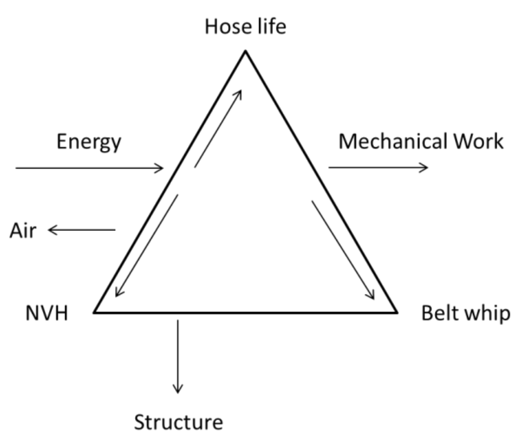


Figure 2: Problem Approach

When analyzing the problem, there were three ways that could affect the balance of hose life, NVH and belt whip. The robustness of each component could be enhanced in order to reduce NVH and belt whip while ensuring hose integrity. The paths in which the energy travels along can be altered in order to limit the variables of NVH, belt whip and hose life. Lastly, it is possible to change the input of the energy by changing the type of compressor used. This concept was overlooked during concept development and selection. When analyzed and scored, it was determined that changing to a screw compressor is not a currently viable solution. For details on the scoring of the screw compressor and all other original concepts along with details on how scoring criteria was created and the house of quality, refer to Appendix.

After determining that the current design path could not be changed by replacing the reciprocating piston cylinder compressor with a screw compressor, the hose life constraint created the need for new design solutions. The first solution NFI offered was to create a brand new concept that was original and could solve all three issues with the current bus line. The second solution was to ignore the current design approach and instead, provide research into future technologies that may not be currently available, but could be implemented into future designs. The third was to of follow the current design as well as consider future designs, and integrating new technologies.

Due to the basis of the customer agreement with NFI, it was determined the project would continue with the concept screening and scoring matrices and the associated designs that were produced. Also, preliminary research and background information about designs and technology that will be implemented into future bus manufacturing and the possibility of recommending different hoses for future considerations is to be included. Both current and future considerations will be discussed in subsequent sections of the report.

3. Details of the Design

The final design was selected by using the concept screening and scoring from the Concept Development Report. It was determined that a vibration absorbing material is the most suitable solution to reduce NVH and a torsional vibration damping pulley is to be used to reduce belt whip. Information on how these components operate along with the details of these components and their assembly into the current bus system are discussed in subsequent sections.

3.1. Vibration Absorbing Materials

When determining an appropriate damping method for a machine or mounting, the consistency and strength of the damping material needs to be considered. The mounting material is generally hard for machine tools and machining centers and soft for components such as generators, pumps or compressors. As a result, rubber is the most widely used material for vibrational damping. Due to the problem involving the ACC on the Xcelsior bus line, a soft vibration absorbing material is desired to reduce vibration and minimize other structural design changes [2].

Before a suitable vibration material can be selected, the source of vibration needs to be identified clearly. Vibration isolation is to first identify the source of the vibration and what its vibration is interfering with. If the interfering frequency of the compressor and the natural frequency of the damper can be measured, the frequency ratio can then be calculated as the ratio of compressor frequency and damper frequency.

$$freq.ratio = \frac{compressor\ frequency}{damper\ frequency}$$

As the frequency ratio is increased, the isolation increases. Then the isolation properties of the damping material limit the build-up of vibrations, and instead vibrations are absorbed through the damping material.

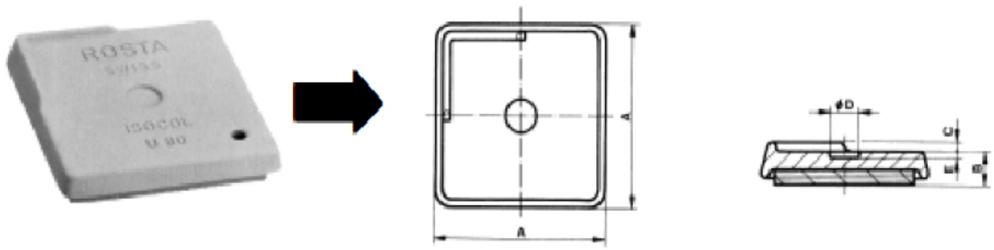
For the final design, ROSTA Inc. provides a variety of solutions to vibration isolation and damping. The rubber damping mounts absorb the vibrations and oscillations created by the source through the rubber's molecular friction. The resulting friction creates an energy loss which is dissipated in the form of heat. ROSTA's materials allow for high energy loss which increases damping on the ACC. However, we do not know the compressor frequency and therefore recommend a final design based on appropriate mass ratings for vibration absorbing materials [2].

Our final design recommends the ROSTA Anti-Vibration Mounting Type ISOCOL U 50. This model was chosen based on the current ACC weighing 52 kg. The resulting force created by this weight is as follows.

$$Weight = mass\ x\ gravity = 52\ x\ 9.81 = 510.12\ N$$

The ISOCOL U 50 is capable of handling loads up to 1500 N. The mounting plate weighs 0.15kg. The base of the plate is a 60 mm x 60 mm square, 14 mm thick. The corner retaining fixture is L shaped and dimensions and details of the damping plate can be found in Figure 3.

ISOCOL U



ISOCOL U

Art. Nº	Type	Load	A	B	C	D	E	Weight in kg
05 040 001	ISOCOL U 50	– 1500 N	60	14	3	11	2	0.15
05 040 002	ISOCOL U 80	1200 N – 3800 N	90	15	3	14	2	0.40

Figure 3: Details of ISOCOL U damping plate. [2] Used with permission

Due to the relatively large size of the ACC compared to the mounting plate, and the need for the ISOCOL U 50 plate to be as effective as possible, it's recommended to install 4 ISOCOL U 50 mounting plates. The 4 plates would then be mounted on the 4 corners of the underside of the ACC to absorb the maximum amount of vibration.

This particular model was chosen due to its specifications to increase damping and reduce noise transmission through substructures created by the ACC transmitted to the bus structure. The ISOCOL anti-vibration mounting units are specified for the medium natural frequency band of 15 to 30 Hz. Note that the precise values of vibration of the ACC are not known and it is assumed that the ISOCOL U50 is a viable solution based on its specified value for weights mounted to the plate. Therefore, the target specification of a reduction of 2-4 dB cannot be determined without adequate testing.

3.2. Torsional Vibration Dampers

Torsional vibration along the crankshaft is inevitable for all internal combustion engines. These vibrations are especially apparent on diesel engines in comparison to petrol engines due to higher compression ratios. During the combustion process inside a typical internal combustion engine, the pressures within the cylinder walls are constantly changing, thus forces transmitted through the crankshaft vary. The forces due to combustion which drive the crankshaft are what drive the belts via a crankshaft pulley, located on the front of an engine. The torsional vibrations generated from the non-uniform force are a function of engine speed. If this vibration cannot be controlled it may result in transmitted vibration to the drive belt system. These torsional vibrations, in combination with the overall vibration of the entire engine, contribute to issues within the drive belt system such as belt whip [3].

Belt whip is a result of the natural frequency of the belt matching up with the frequency of torsional vibrations or transverse vibrations of the internal combustion engine. Another factor to consider is the frequency of vibration at the pulley being powered. In NFI's current Xcelsior bus line, a reciprocating piston cylinder compressor is powered producing torsional and transverse vibration. In order to eliminate belt whip completely, the belts must run without any frequency of vibration to the drive belt system. However, this is not possible in reality.

There are two types of torsional damping pulleys. For the first to reduce the amount of vibration transmitted along the crankshaft engine, manufacturers generally incorporate a torsional vibration damper within the crankshaft pulley with their design. The crankshaft vibration damper includes a rubber material in between the inner and outer parts of the pulley which is specifically designed to absorb torsional vibrations at certain engine frequencies [4].

A second and more effective type of torsional damping is known as the de-coupled torsional vibration damping pulley. The dampers with de-coupled pulleys are designed to withstand greater torsional vibration which is ideal for diesel engines. The operating principles of the de-coupled damper are similar to the principles of a typical crankshaft damper with the exception that the belt pulley is de-coupled from the hub and flywheel. As seen in the cross sectional figure 4, the belt pulley has the ability to rotate with respect to the hub and flywheel. One side of the pulley rests on the hub with bearings while the opposite side is coupled via an elastomeric material which serves as an isolator. The elastomer material is designed to absorb torsional vibrations at two locations, between the hub and flywheel, and between the hub and belt pulley [4].

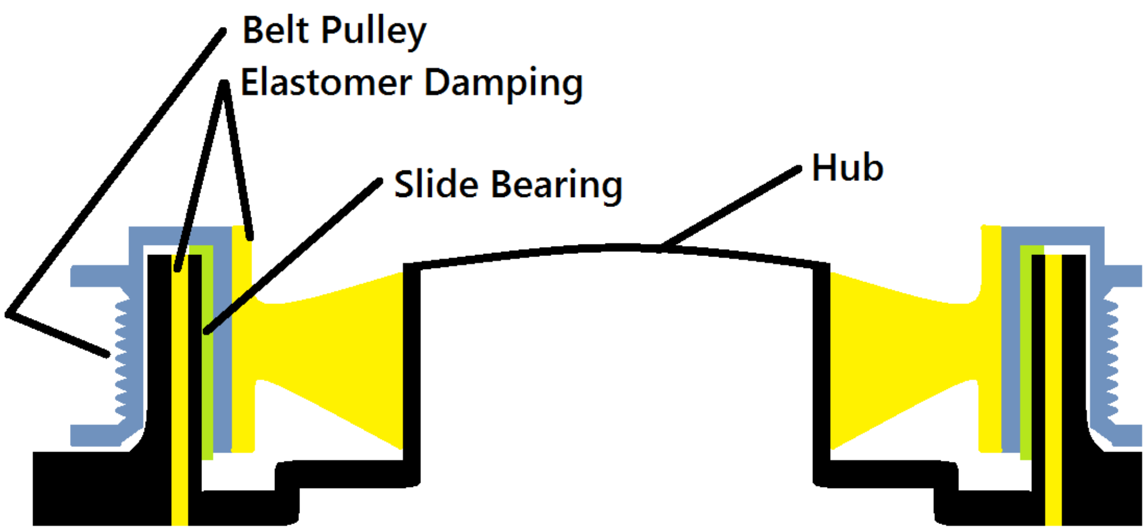


Figure 4: De-Coupled Torsional Vibration Damper Pulley

For the final design, Hasse & Wrede was chosen as they offer a wide variety of custom Visco-Damper crankshaft pulleys for unique applications. Hasse & Wrede offer both types of torsional damping pulleys (coupled or de-coupled) and the selection of the appropriate type depends on the user's application.

For the final design, it is recommended to use the design under the name of "Visco-Damper with integrated pulley and hub for commercial vehicle engine" rated at 419 kW (562 hp), which is a de-coupled type of torsional vibration damper as seen on their website. Between all of the pre-set designs available, the de-coupled damper rated at 419 kW is the best suited for the Cummins ISL motor used in the Xcelsior bus line in terms of power output. This type of damper is maintenance free with the exception of the bolts used to fasten it to the engine and it serves as a big advantage over its alternatives. The design also recommends to get in touch with Hasse & Wrede for custom sizing and appropriate RPM ratios between the crankshaft and the other components of the drive belt system [4]. A visco-damper of this type (not the exact size) is depicted in Figure 5.

Figure 5: Actual De-coupled Damper. [4] Used with permission.

3.3. Assembly

Before explaining the details of assembly, the current layout of the engine compartment is shown to give a visual representation. Figure 6 shown depicts the CAD drawing of the engine compartment showing the crankshaft pulley, the ACC, the mounting plate for the compressor, the ACC hoses, and the drive belt from the crankshaft to the ACC.

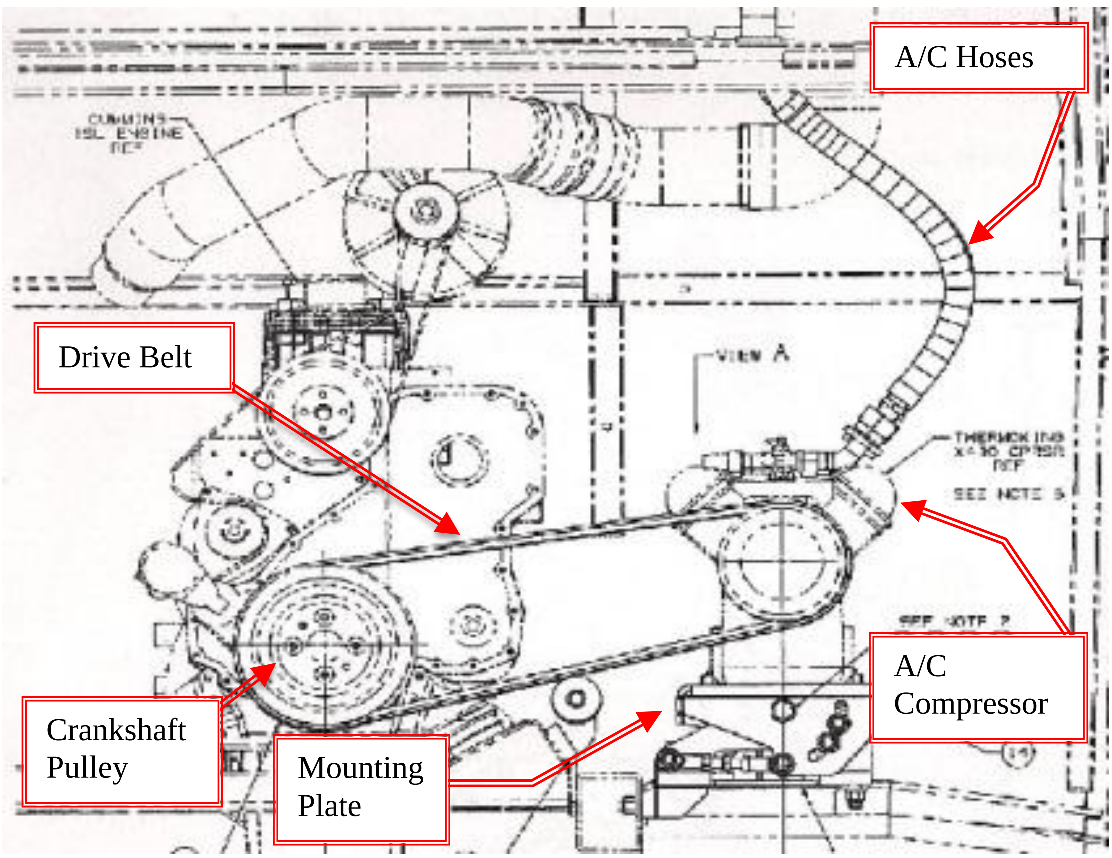


Figure 6: CAD drawing of current engine layout [5]. Used with permission

Figure 7 illustrates the bus engine compartment showing exactly the same layout as the CAD drawing but it gives an actual view of the engine for better visualization.

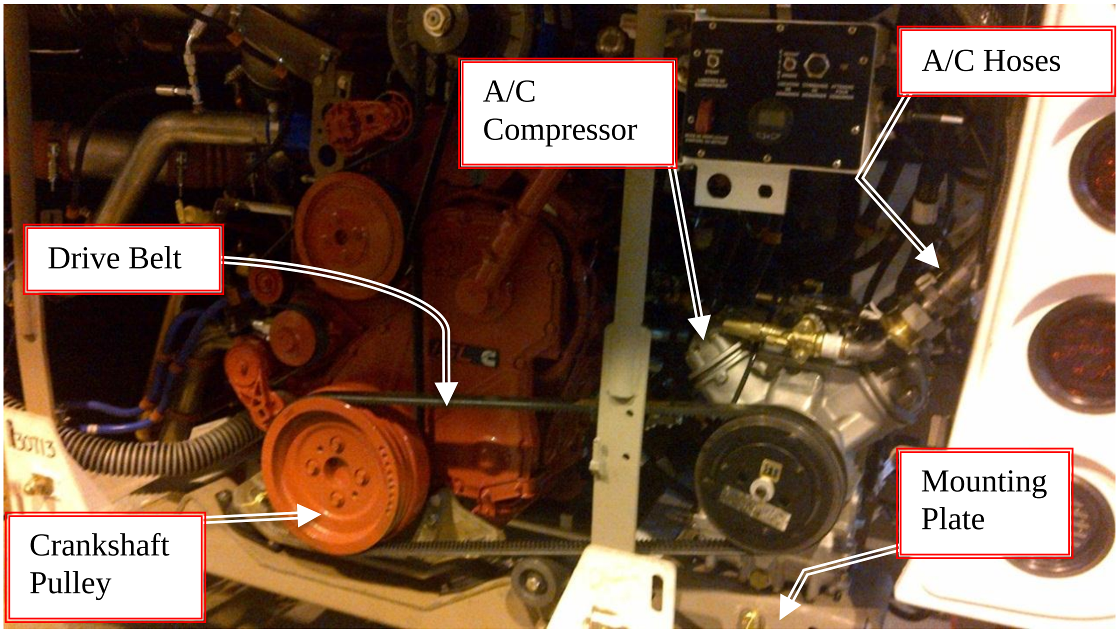


Figure 7: Current view of engine compartment. Used with permission

The assembly of the design is straight forward and simple and does not require too much work for implementation because all components are easily accessible in the rear engine compartment of the bus. To reduce belt whip, a damping pulley is applied at the crankshaft. To install this part, the in-use pulley, which is already on the crankshaft, is unbolted and removed. The damping pulley is then put in place of the old pulley and bolted on in the same manner as the old pulley.

To reduce the amount of vibrations from the compressor, 4 vibration damping mounts are to be placed on the 4 corners of the underside of the compressor, then mounted onto the steel mounting plate. To install the mount, the A/C hoses must be disconnected from the compressor and the compressor must be unbolted from the mounting plate. Once this is done, a lift will be used to hoist the compressor off the mounting plate. With the compressor off of the mount plate, the vibration damping mount will be placed on the steel mounting plate in the proper position. The compressor would then be lowered back down on to the vibration damping mount and would then be bolted back on the steel mount plate and the hoses connected back on to the compressor.

3.4. Cost Analysis

The design uses two primary components, the vibration absorbing mounting plates and the torsional damping pulley. These components are readily available and no fabrication or manufacturing costs are needed. The time taken to integrate the components into the current engineering drawings and CAD models will not be taken into account. Instead, the assembly is all done by NFI in house and therefore will be approximated at 5 hours at $30/hr. Maintenance done by NFI's customers is done by the customers in their shops, and therefore those costs and not considered. Details for the final cost per unit are found in the following table.

Table 1: Cost of components per bus

Item	Cost (CAD)
ISOCOL U 50 Damping Plate	99.20
Torsional Damping Pulley	350.00
Assembly	150.00
Total	599.20

We see the total cost per bus is $599.20. No budget was originally specified by NFI.

4. Future Design Considerations

As technology continues to evolve and new methods of damping and reducing belt whip are created, changes will be made to how the ACC system will be powered and how it will be damped. Also, as the current hoses are rigid during operation, possible alternatives and information on hoses will be discussed for possible future use. While a screw compressor was ruled out as a current design change, it can still be considered as a future design option. Due to there being no current timeline as to when the following future considerations could be implemented, no cost analysis can be considered for this section of the report.

4.1. Electronic Damping

When it comes to vibration control, a lot of focus has been on using electronics to give a faster response to changing conditions that can add to the amount of vibrations experienced. There are a few different applications that have come about from the research into electronic vibration control. These include electronic suspension in vehicles instead of standard hydraulic systems, electronically controlled air suspension, which is mainly used to control ride heights in vehicles for smoother operation, as well as modular vibration isolation systems, which are mainly used in labs for testing and research equipment.

In the electronically controlled suspension, each shock absorber has its own individual actuator. A central control module is fed data from sensors placed around the vehicle which it then analyzes and transmits signals to each of the actuators. This allows each shock absorber to react individually to the conditions in order to minimize vibrations. However, this option of electronic damping would not be the best option for vibration control on the compressor of the bus because it would require a high quantity of time and money to scale down the ACC system.

The electronic suspension system is outfitted to be used over the area of an entire vehicle and the compressor vibration problem is focused to a smaller localised area [6].

The electronically controlled air suspension system is currently being used mainly as a height control system again in vehicles. Height sensors are placed between the axle and chassis of the vehicle. As the distance between the axle and chassis varies so too does the voltage signal from the sensor controlling the amount of air supplied to the air springs. This would be a viable option to solve the compressor vibration problem given that appropriate sensors can be used to detect the vibrations so that the air springs can receive the proper amount of air to counter act the vibrations [7].

The third form of electronic damping covered is the modular vibration isolation system. This system consists of multiple modules that act as mounts for the component that needs the damping. At this time this system is used in static conditions in labs and research facilities for stationary testing equipment. If the modules could be altered in such a way that pieces could be mounted to them in a dynamic situation so that they can be used outside of a lab, they would be a very good option to reduce the vibration from the localised compressor [8]. Figure 8 is a picture of the modular vibration isolation system. The component requiring damping is placed on top of the two long beams seen in the following figure. The device sitting on top of the dampers is the control module. The control module can be mounted anywhere nearby as it’s connected through wires to the damping bars. Information is sent from the dampers to the control module which analyzes the data and then sends back a signal to the dampers telling them how much damping is needed.

Figure 8: Modular Vibration Isolation System[8] Used with permission.

All three of these options are future solutions to reduce excessive vibration. All three options need some adjustments and outfitting in order to be used in the smaller, localised area of the compressor. At this stage, the best option is the modular vibration isolation system as it would take the least amount of work to make the transition from its current use to the required use of reducing the vibration produced by the compressor of the bus.

4.2. Hoses

When determining a recommendation for a new hose, a set of desired hose characteristics are first outlined. These desired characteristics are as follows:

- Zero leak rate
- Flexible (able to withstand small bend radii)

- High operating temperature
- High operating pressure ~500 psi (discharge pressure is 470 psi)
- Compatibility with R-134a and R-407a refrigerants

Currently the AC compressor hoses used by NFI exhibit the following:

- Negligible rate of effusion.
- High operating temperatures
- Operating pressures up to 470 psi.

The current hose serves as a limitation to a rigid ACC mount, which is currently producing vibration issues transmitted through the frame of the bus. Due to embrittlement of the compressor hoses upon operation of the ACC system, the current hose is known to be prone to failure when in combination with a dynamic ACC mount. Allowing a non-rigid AC compressor mount will theoretically eliminate vibration transmitted to the frame of the bus if designed properly. Also, in theory, any flexible hose subjected to large internal pressures will become brittle. Therefore, flexible hoses which will not fail should be considered.

In the search for an appropriate hose, the specifications of the hose must be defined. The desired characteristics of the hose are to have a zero rate of effusion, be flexible enough to withstand small bend radii (to appropriately route the hose) even at high pressures, exhibit high operating temperature, exhibit high operating pressure, not fail under dynamic loading while under pressure, and be compatible with R-134a and R-407a refrigerants. The hoses must also be properly sized for the fittings leading to the ACC.

In the current market, the best option for ACC hoses would be the Goodyear Galaxy 4890 ACC Refrigerant Hose. The Galaxy 4890 meets SAE J2064 standards and exhibits the lowest permeation rate out of all ACC hoses on the market. The Galaxy 4890 exhibits a permeation rate of 0.5 kg/m^2 per year, an operating temperature range between -40^{o}C and +135^{o}C, a moisture ingression rate of 0.027 g/cm^2 per year (lowest on the market) and a very low capable bend radius of 2.5" (for a nominal hose size of 5/8"). The Galaxy 4890 is also compatible with most refrigerants including R-134a and R-407a. Figure 9 illustrates the composition of the Galaxy 4890 hose [9].

Figure 9: Goodyear Galaxy 4980 Hose. [9] Used with permission.

4.3. Screw Compressor

For future considerations of bus manufacturing a different compressor is worth considering. NFI has a professional relationship with Thermo King as a supplier for ACCs. As a result it was determined that alternative compressors manufactured by Thermo King would be considered.

4.3.1. S391/S616 Screw Compressor

Thermo King screw compressors offer a variety of features benefiting the client. The screw compressors incorporate fewer moving parts in contrast to the reciprocating compressors. This implies lower maintenance and replacement costs. The screw compressors incorporate safe environmental refrigerants. They are capable of programming capacity control in order to save on fuel consumption. Most importantly, these compressors offer a reduction in noise and vibration in comparison to reciprocating compressors. The Thermo King screw compressor is designed specifically for bus line applications [10].

Lab tests performed by Thermo King have determined lower noise levels. At 1400 rpm a microphone located a foot from the rear of the compressor measured a decrease in noise by 2.3 db. At 2200 rpm the reduction in noise was 1.4 db. Table 2 lists all the experimental data collected for the noise level testing off the ACCs. Figure 10 illustrates the experimental setup for testing. [9]

Table 2: Test results for noise levels generated from ACC's. [10] Used with permission

Compressor	Microphone Position	Speed (rpm)	Noise Level (dba)
Screw	A	1400	79
6 Cyl. Reciprocating	A	1400	87.5
Screw	B	1400	87.2
6 Cyl. Reciprocating	B	1400	89.5
Screw	A	2200	87.9
6 Cyl. Reciprocating	A	2200	88.7
Screw	B	2200	91.3
6 Cyl. Reciprocating	B	2200	92.7

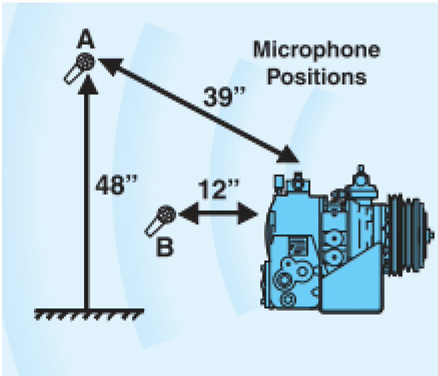


Figure 10: Experimental setup for noise level testing. [9] Used with permission

The screw compressors produce much lower vibrations than the reciprocating compressors. Tests performed by Thermo King indicate that vertical accelerations are approximately 1/3 of those experienced by reciprocating compressors. Furthermore the torque produced is lower and fluctuates less over the same time period. These results are evident in Figure 11. [9]

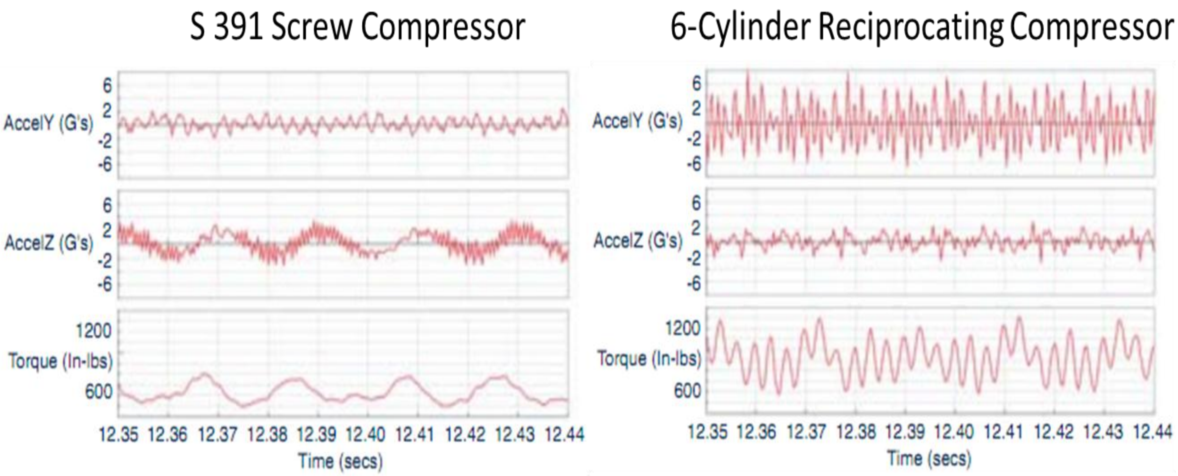


Figure 11: Vibration and torque comparison between screw and reciprocating compressors. [10] Used with permission

The capacities of each refrigerant in both the S391 and S616 compressors increase linearly with respect to rpm. These capacity ranges are depicted in Figure 12 and Figure 13.

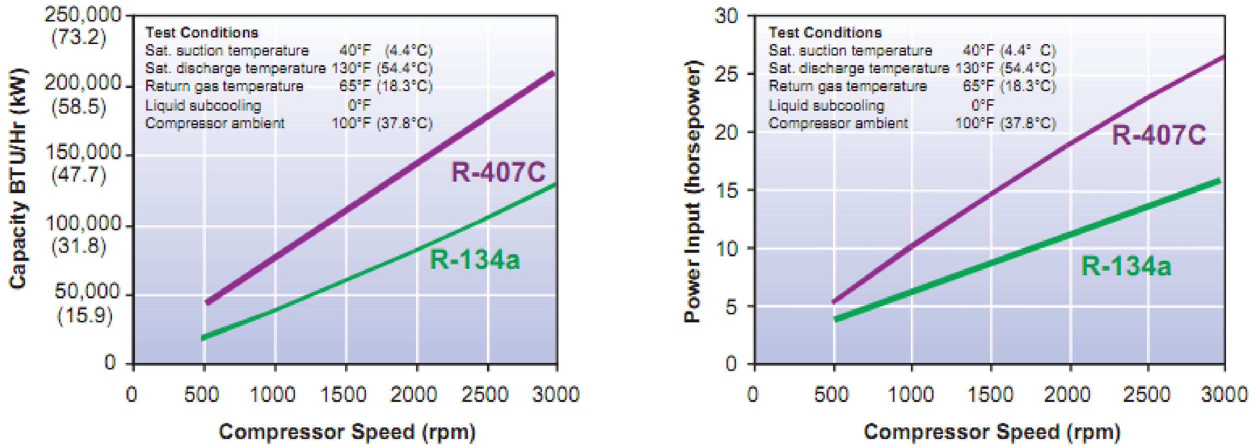


Figure 12: Capacity and input power vs. rpm for S391 Screw Compressor. [10] Used with permission

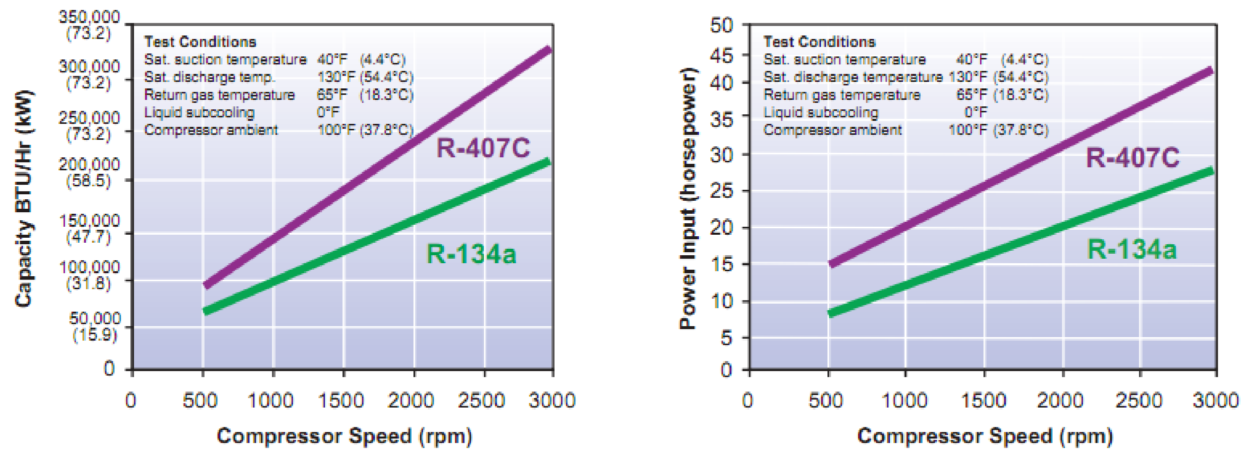


Figure 13: Capacity and input power vs. rpm for X690 Reciprocating Compressor. [10] Used with permission

Error! Reference source not found. Table 3 illustrates the range of capacities for each ompressor and refrigerant at high and low rpms.

Table 3: Compressor capacity ranges for different refrigerants

Compressor	Refrigerant	Capacity @ 500 RPM (BTU/Hour)	Capacity @ 3000 RPM (BTU/Hour)
S391	R-407C	50000	210000
S391	R-134a	20000	130000
S616	R-407C	100000	350000
S616	R-134a	70000	220000

Table 4 outlines the specifications for the two available screw compressors and the currently employed reciprocating compressor.

Table 4: Specifications for screw and reciprocating compressors. [11] [12] Used with permission

Compressor:	Model S391	Model S616	Model X430
Type	Helical Lobed Screw	Helical Lobed Screw	Reciprocating Compressor
Displacement	23.86 cu in/rev (391 cu cm/rev)	37.59 cu in/rev (616 cu cm/rev)	30 cu in (492 cu cm)
Number of Cylinders	6	6	4
Max BHP	24 BHP (R134a)	28 BHP (R134a)	19 BHP (R134a)
	35 BHP (R-407C)	41 BHP (R-407C)	29 BHP (R407C)
			29 BHP (R22)
Max speed	3000 rpm	3000 rpm	3000 rpm
Refrigerant	HFC (R-134a or R-407C)	HFC (R-134a or R-407C)	R-134a R22, R-407C
Oil Separator	Integrated	Integrated	8.9 pints (4.2 liter)
Oil Pump	Integrated on discharge side	Integrated on discharge side	Gerotor type
Oil Type	POE SOLEST 120	POE SOLEST 120	TK 67-404 (R22)
			TK 66-6828 (R-134a)
			TK 66-6828 (R-407C)
Maximum Tilt	10 degrees any direction	10 degrees any direction	10 degrees any direction
Drive Method	Belt or Direct	Belt or Direct	Belt or Direct
Max discharge temp	300 degrees F	300 degrees F	325°F (162.8°C)
Max Belt Side Loading	300 lbs. (136 kg)	300 lbs. (136 kg)	300 lbs (136 kg)
Weight	147 lbs. (66.8 kg) – including oil, service valves and clutch	171 lbs. (77.2 kg) – including oil, service valves and clutch	115 lbs (52.2 kg)

Table 4 shows that both the screw and reciprocating compressors have similar operating conditions. This implies that implementation of a screw compressor is suitable for the design of the HVAC system in the Xcelsior bus line.

With the addition of a screw compressor it is likely that the production of noise and vibration will be much lower than with the currently employed reciprocating compressor. This is a result of lower accelerations and torque originating from the screw compressor. This will result in lower levels of vibration moving structurally through the frame of the bus. Minimizing the source of vibrations will result in a lower level of noise within the passenger compartment of the bus. The following sections show screening and scoring of the screw compressor for future considerations.

4.3.2. Screening and Scoring

It is worth looking into screening and scoring again based on a new design rather than reworking a compressor into the existing design.

Table 5: Concept Screening for Future Considerations

CONCEPT SCREENING							
	CONCEPTS						
	NVH						
Selection Criteria	**Pivot Mount w/ Air Springs**	**Composite Material**	**Soundproofing Material, Entire Engine Compartment**	**Soundproofing Material, Compressor**	**Vibration Absorbing Material between ACC and Mount**	**Shock Absorber Mounts**	**Screw Compressor**
Minimizes Cost	-	+	-	0	0	0	+
Lightweight	0	+	-	0	+	+	+
Reduces Noise Level	+	-	+	+	+	0	+
Is Manufacturable/ Available	+	0	0	0	+	+	+
Is Durable	-	+	-	-	+	0	0
Easy to Service and Maintain	-	0	-	0	+	+	0
Easy to Integrate	-	+	-	0	+	+	0
Long Belt Life	+	0	-	-	0	0	0
Sum +'s	3	4	1	1	6	4	4
Sums 0's	1	3	1	5	2	4	4
Sums -'s	4	1	6	2	0	0	0
Net score	-1	3	-5	-1	6	4	4
Rank	5	4	7	5	1	2	2
Continue?	**No**	**No**	**No**	**Combine**	**Yes**	**Yes**	**No**

When screening a screw compressor shows a much better rating for approval. Although it still does not appear to be the best concept it still needs to be scored against the preferred concept. Table 6 illustrates the scoring with the screw compressor as a new design.

Table 6: Concept scoring for future considerations

CONCEPT SCORING									
		CONCEPTS							
		NVH							
Selection Criteria	**Weight**	**Vibration Absorbing Material between ACC and Mount**		**Shock Absorber Mounts**		**Compressor Mounted to Engine and Soundproofing Material, Compressor**		**Screw Compressor**	
		rating	weighted score	rating	weighted score	rating	weighted score	rating	weighted score
Minimizes Cost	6	3	18	3	18	1	6	4	24
Lightweight	1	3	3	3	3	1	1	3	3
Reduces Noise Level	24	3	72	2	48	4	96	4	96
Manufacturable /Available	11	3	33	3	33	2	22	3	33
Is Durable	11	3	33	2	22	2	22	3	33
Easy to Service and Maintain	10	3	30	2	20	1	10	3	30
Easy to Integrate	17	3	51	2	34	2	34	3	51
Long Belt Life	19	3	57	3	57	5	95	3	57
	Net score	297		235		286		327	
	Rank	2		4		3		1	
	Continue?	No		No		No		Yes	

When analyzing the scoring matrix it is clear that replacing the reciprocating compressor with a screw compressor provides a much better benefit. With the ability to reduce the vibration due to the input energy into the system a screw compressor reduces the NVH while reducing the cost as well while maintaining integration ease. As a result it is recommended for future considerations that a new compressor is used to reduce NVH while maintaining hose life.

5. Summary

This report outlined the final design components required to reduce NVH and belt whip on the Xcelsior bus line. Four ROSTA ISOCOL U50 mounting plates are recommended to reduce and absorb the vibration created by the ACC. The Visco-Damper with integrated pulley and hub for commercial vehicle engine provided by Hasse & Wrede is recommended to reduce belt whip during operation. A cost per bus for both components including assembly was determined to be 599.20 CAD.

This report also discussed future considerations and recommendations for future designs. Modular damping is recommended to reduce and hopefully eliminate NVH in the future. Changing to Galaxy 4890 hoses is recommended for future use. A screw compressor can be implemented in future use as an alternative to the current reciprocating piston cylinder compressor.

References

[1] New Flyer Industries. (2011). "History." [Online] Available: http://www.newflyer.com/index/history [Nov. 18th 2011]

[2] ROSTA Inc. (2011). "Anti-vibration Mounting Type ISOCOL/Type ISOCOL U." [Online] Available: http://www.rosta.ch/media/prd/Gummifeder-Technologie/ISOCOL_U/ downloads-ENG/2010_Anti-vibration_Mounts_Type_Isocol.pdf [Oct. 26th 2011].

[3] Fluidampr. (2011). "Why your engine needs a damper." [Online] Available: http://www.fluidampr.com/HOWITWORKS.htm [Oct. 28th 2011]

[4] Knorr-Bremse. (2011). "Tosional Visco-Dampers." [Online] Available: http://www.hassewrede.de/en/produkte/viscodmpfer/viscodmpfer_1.jsp [Nov. 2nd 2011]

[5] New Flyer Industries. *Engine Schematic*. New Flyer Industries, Winnipeg. [Sept. 20th, 2011]

[6] BMW Technology Guide. (2010). "Electronic Damper Control (EDC)." [Online] Available: http://www.bmw.com/com/en/insights/technology/technology_guide/articles/electronic_damper_control.html [Nov. 14th 2011].

[7] Dunlop Systems and Components. (2010). "Electronically Controlled Air Suspension (ECAS)." [Online] Available: http://www.dunlopsystems.com/product.php?page=3&sub=10&show=10 [Nov. 15th 2011].

[8] Herzan High Performance Environmental Solutions. (2011). “AVI Series.” [Online] Available: http://www.herzan.com/products/active-vibration-control/avi-series.html [Nov. 15th 2011]

[9] Veyance Technologies Inc. (2011). Transportation – OE Products: Products: Air Conditioning Hose – Galaxy. *Galaxy 4890 SLE A/C Refrigerant Hose.* Available: http://www.goodyearep.com/ProductsDetail.aspx?id=6056

[10] Ingersoll-Rand Co. (2008). S391/S616 Screw Compressor. *ThermoKing.com*. Available: http://www.thermoking.com/pdf/50895_ScrewCompressor.pdf.

[11] Thermo King. (2011). Products: Bus: Technology: Bus Air Conditioning Screw Compressors And Clutch Specifications. *ThermoKing.com*. Available: http://www.thermoking.com/tk/index.asp.

[12] Thermo King. (2011). Products: Bus: Technology: Bus Air Conditioning Reciprocating Compressor And Clutch Specifications. *ThermoKing.com*. Available: http://www.thermoking.com/tk/index.asp.

Appendix

A.1. Concepts

Concept designs are divided into two categories; addressing NVH and addressing belt whip. These designs were developed to eliminate at least one component of the problem.

A.1.1. Pivot Mount with Air Springs

Combining a pivot mount with air springs would prevent vibration from the ACC to travel through the structure of the bus. The pivot mount would provide the ACC with the ability to oscillate freely from side to side while preventing it from vibrating forward and back. The air springs would dampen the vibrations resulting in a reduced NVH. The air springs would require integration within the existing bus line to maintain a supply of compressed air.

A.1.2. Composite Material

The ACC is currently rigidly mounted to the frame of the bus. The composite material design concept mounts the ACC on a composite material and then mounts it to the bus frame. The composite material is expected to dissipate some of the vibration created by the ACC.

A.1.3. Sound Proofing Material

This design concept evolved into two separate components. The first idea was to attach sound proofing material to the entire interior of the engine compartment. The alternative approach was to solely cover the ACC. Sound proofing material may reduce the amount of noise produced in the engine compartment. The material is known to absorb vibrations and reduce generated noise.

A.1.4. Vibration Absorbing Material

This design concept is similar to the pivot mount with air springs. It removes the rigidly mounted ACC and uses a vibration absorbing material between the frame and ACC. A damping plate will allow the vibrations generated by the ACC to be absorbed into the damping plate reducing the vibrations travelling along the bus structure.

A.1.5. Shock Absorber Mounts

This design concept is again similar to the pivot mount with air springs design. This design is different however by not using a pivot mount. There will be 4 shock absorbers placed on the mounting plate, all of which will be an equal distance away from the center of gravity of the ACC.

A.1.6. Compressor Mounted to the Engine

Mounting the compressor to the engine is expected to reduce the belt whip. Fastening an L bracket supported by a gusset to the engine provides a platform for the ACC to be mounted to. The ACC would then oscillate with the engine causing a reduction in offset vibration between the crankshaft pulley and the ACC pulley. This in turn would reduce belt whip and increase belt life.

A.1.7. Idler Pulley with Spring

Combining and idler pulley with a spring would maintain tension on the belt and reduce the belt whip. The idler pulley would be attached to a bracket mounted to the frame of the bus. For the application of this design concept, Gates ‘rules of thumb’ would need to be taken into consideration.

A.1.8. Guide Pulleys

Guide pulleys would act as vertical displacement constraints on the belt between the crankshaft pulley and the ACC pulley. They would be mounted similar to the idler pulley design. Two pulleys located above and below the belt would fixate its vertical position at that set point reducing belt whip.

A.1.9. Damping Pulley

The damping pulley would be attached to the crankshaft of the engine. It minimizes the vibrations transferred to the crankshaft pulley due to the engine. An example of a damping pulley is the Linnig pulley that NFI referred to. It provides a large reduction in belt whip.

A.2. Selection

In order to determine the best concept, the concepts first need to be screened. Concepts passing the screening will be scored, along with possible scoring two concepts that failed the screening. The concept criteria for screening and scoring and the weights of the scoring criteria are derived through the House of Quality (**HOQ**).

A.2.1. House of Quality

The HOQ was designed to relate customer needs to target specifications. Figure 14 depicts the HOQ designed for this project.

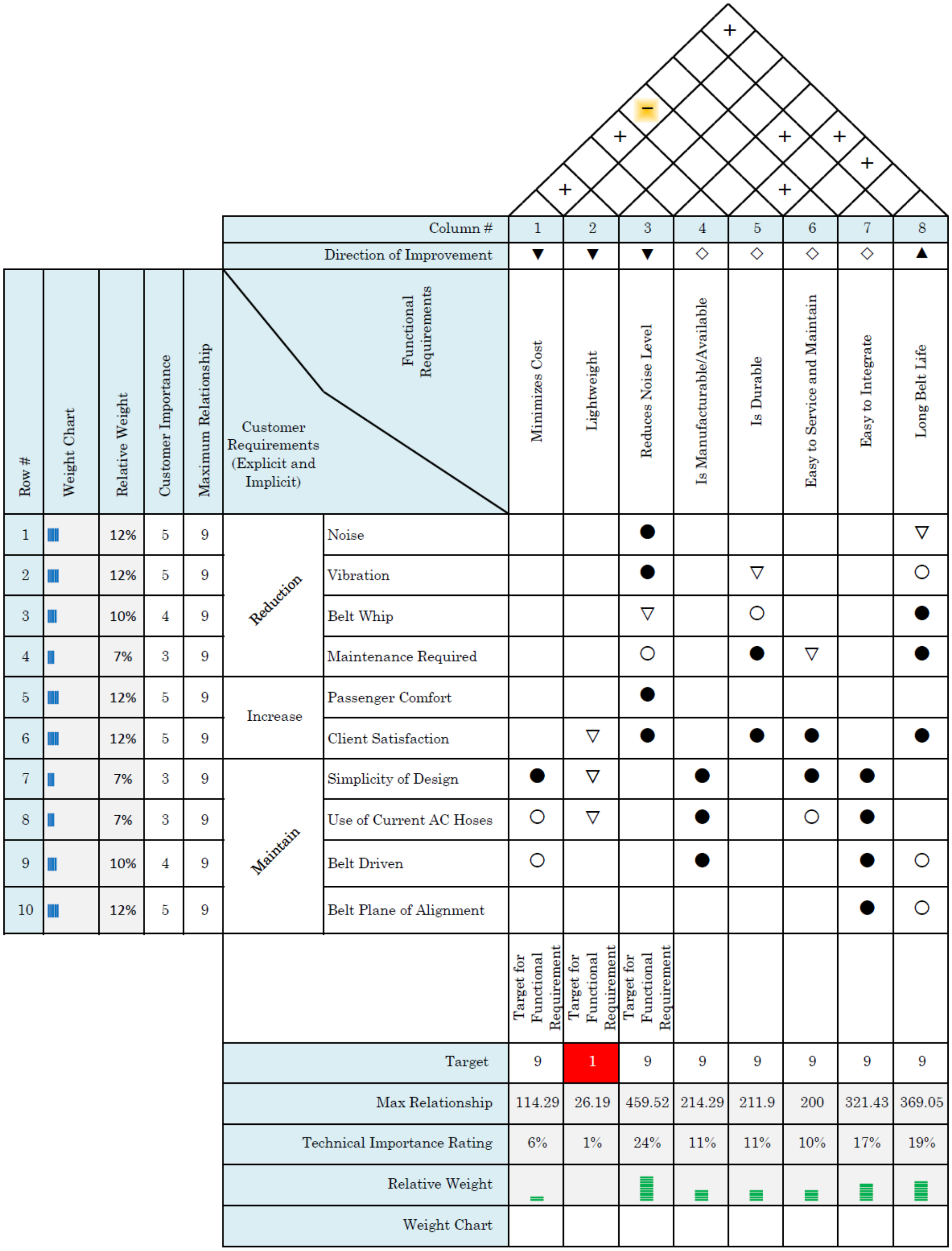


Figure 14: House of quality

The process of creating the HOQ illustrated in the previous figure started with listing out the requirements of the client. Since the project is a re-design project, the needs were put into the three main categories: reduction, increase, and maintain. Certain aspects NFI's current design will need to be reduced, increased, or maintained in terms of quantity in order to be meet the overall needs of our client. From the previous page, it shows the needs of the clients listed along the vertical axis of the HOQ matrix. Further to the left of the list of needs is a rating of customer importance on a scale of 1-5, which determines the relative weight of the list of customer requirements. The ratings used in the HOQ were as specified by the client. The next step in creating a house of quality is coming up with a list of criteria that will be used to rate all of the design concepts. The list of criteria should reflect characteristics of a concept that will meet all of the needs of the client. The previous figure illustrates the criteria on the top horizontal axis of the HOQ matrix. After coming up with a set of criteria, the relationship between criteria and the client needs are discussed and determined as a group and input into the body of the HOQ matrix. The intersection point of a specific criteria and a specific customer need will contain a solid circle if they share a strong relationship, a hollow circle if they share a moderate relationship, an upside down triangle if they share a weak relationship, and no symbol if they do not relate to each other. After the entire HOQ matrix has been filled out, the weight of each criterion for the concept screening and concept scoring matrix is determined and shown towards the bottom of the HOQ under "technical importance rating".

The criteria used in our HOQ are: minimizes cost, lightweight, reduce noise level, manufacturability/available, durable, easy to service and maintain, easy to integrate, and long belt life. These criteria are then applied to our screening matrix to screen the various concepts.

A.2.2. Screening and Scoring Matrices

The screening matrices illustrated in Tables 7 and 8 are used to determine which design concepts are acceptable based on the set of criteria derived in the formation of the HOQ. The first table contains the concepts the team has developed to resolve the NVH issue and the second table contains concepts developed to overcome belt whip.

Table 7: Concept screening matrix for current designs

CONCEPT SCREENING							
	CONCEPTS						
	NVH						
Selection Criteria	**Pivot Mount w/ Air Springs**	**Composite Material**	**Soundproofing Material, Entire Engine Compartment**	**Soundproofing Material, Compressor**	**Vibration Absorbing Material between ACC and Mount**	**Shock Absorber Mounts**	**Screw Compressor**
Minimizes Cost	-	+	-	0	0	0	-
Lightweight	0	+	-	0	+	+	+
Reduces Noise Level	+	-	+	+	+	0	+
Is Manufacturable/ Available	+	0	0	0	+	+	+
Is Durable	-	+	-	-	+	0	0
Easy to Service and Maintain	-	0	-	0	+	+	0
Easy to Integrate	-	+	-	0	+	+	-
Long Belt Life	+	0	-	-	0	0	0
Sum +'s	3	4	1	1	6	4	3
Sums 0's	1	3	1	5	2	4	3
Sums -'s	4	1	6	2	0	0	2
Net score	-1	3	-5	-1	6	4	1
Rank	5	3	7	5	1	2	4
Continue?	**No**	**No**	**No**	**Combine**	**Yes**	**Yes**	**No**

The criteria are listed along the vertical axis of the both screening matrices and the design concepts are listed along the top horizontal axis. A cell in the body of the matrix contain a "-" if the corresponding concept does not meet the corresponding criteria, a"+" if the concept meets the criteria, and a “0” if a concept somewhat meets the criteria. A “+” will result in a value of 1, a “-” will result in a value of -1 and a “0” is self-explanatory. The score of each concept is totalled and the concepts are ranked against each other. As a group we decided to proceed with the top two concepts from the NVH matrix and top two concepts from the belt whip matrix. The top two concepts from the NVH matrix are: vibration absorbing material between ACC and mount and shock absorber mounts. The top two concepts from the belt whip matrix are: damping pulley and idler pulley with spring.

Table 8: Concept scoring for current designs

CONCEPT SCORING									
		CONCEPTS							
		NVH							
Selection Criteria	**Weight**	**Vibration Absorbing Material between ACC and Mount**		**Shock Absorber Mounts**		**Compressor Mounted to Engine and Soundproofing Material, Compressor**		**Screw Compressor**	
		rating	weighted score	rating	weighted score	rating	weighted score	rating	weighted score
Minimizes Cost	6	3	18	3	18	1	6	1	6
Lightweight	1	3	3	3	3	1	1	3	3
Reduces Noise Level	24	3	72	2	48	4	96	4	96
Manufacturable /Available	11	3	33	3	33	2	22	3	33
Is Durable	11	3	33	2	22	2	22	3	33
Easy to Service and Maintain	10	3	30	2	20	1	10	3	30
Easy to Integrate	17	3	51	2	34	2	34	1	17
Long Belt Life	19	3	57	3	57	5	95	3	57
	Net score	297		235		286		275	
	Rank	1		4		2		3	
	Continue?	**Yes**		**No**		**No**		**No**	

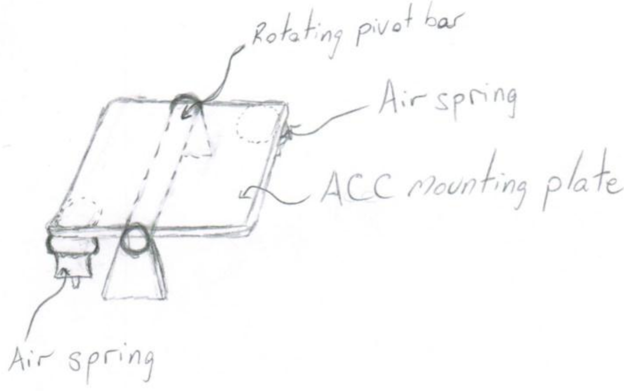
We have also decided to fuse one concept from each matrix to create a new concept which will be evaluated in the concept scoring matrix of the next section of this report. The two concepts which were fused are: compressor mounted to engine and soundproof material on the compressor. Table 7 above illustrates the concept screening matrix for the issue belt whip.

The concepts which passed the screening matrix are now evaluated in the scoring matrix seen in Table 8. The concept which had the highest rating in each matrix will be the reference matrix and contains a rating of "3" for all criteria. Remaining concepts in the same category will contain a value of rating for each criterion with respect to the concept of reference. A rating higher than 3 for a concept corresponding to a specific criterion signifies that the concept meets the criteria more than the reference concept. The weight of each criterion is derived from the HOQ matrix which was discussed in a previous section. To obtain the weighted score of concept for each criterion, the rating is multiplied by the weight of the corresponding criteria. The sum of weighted score for each concept is shown at the bottom of the concept scoring matrix and the concepts are then ranked.

A.3. Original Concept Sketches

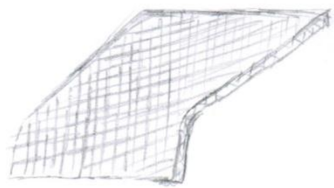
Pivot Mount with Air Spring Supports

Not to scale



This design consists of mounting the ACC on a plate which is attached to a round bar that can pivot from side to side. At two of the four corners of the plate there will be an air spring which will prevent the plate from rotating too far as well as absorbing some of the vibrations that are created by the ACC.

Composite Material



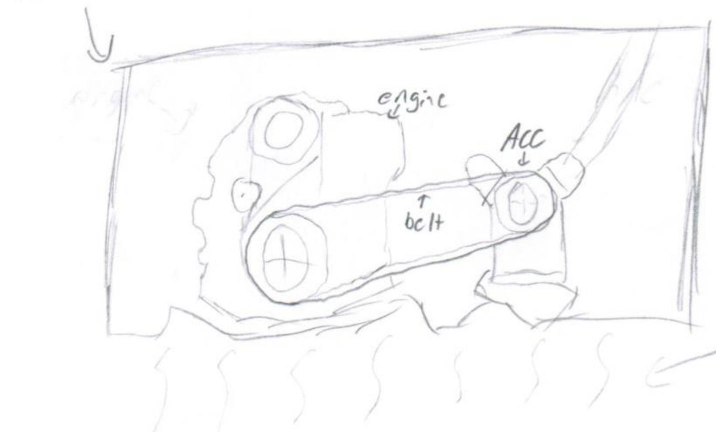
The composite material design just takes the same steel plate design that is used and instead of using steel it uses a composite material that would be lighter and would absorb vibrations better then steel without losing the strength.

Soundproofing Material

2 Options : A - Sound proof entire engine compartment
B - Just soundproof compressor

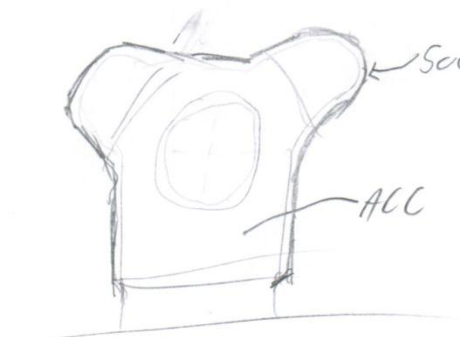
A

Sound proof cover around the entire engine compartment except the bottom.



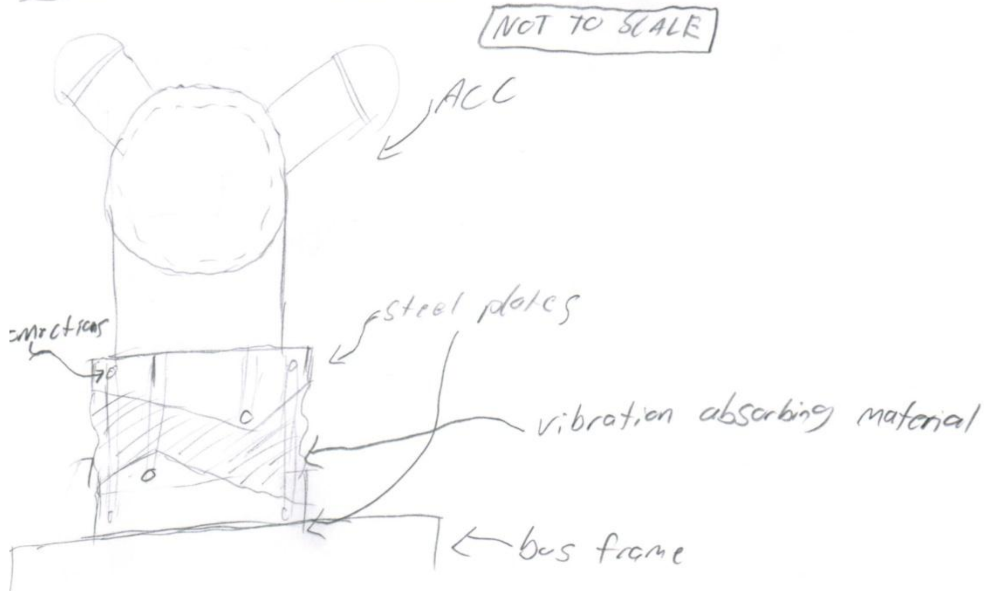
All excess sound is dissipated through the bottom.

B



- Custom fit application to fit the ACC
- Vibration Resistant blankets are already commercially available

Vibration Absorbing Material

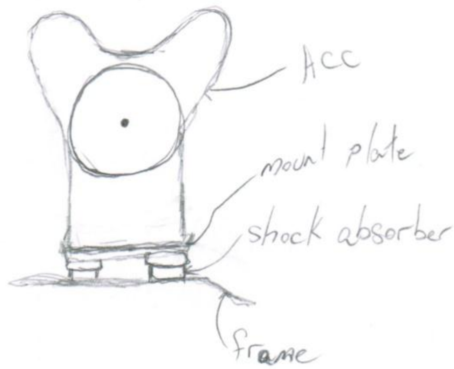


If a material that absorbs vibration can be mounted between steel plates, less vibration would be transmitted to the frame and there should be less NVH in the bus.

ROSTA has a vibration absorbing plate, this shows there are commercially available options if this design is pursued.

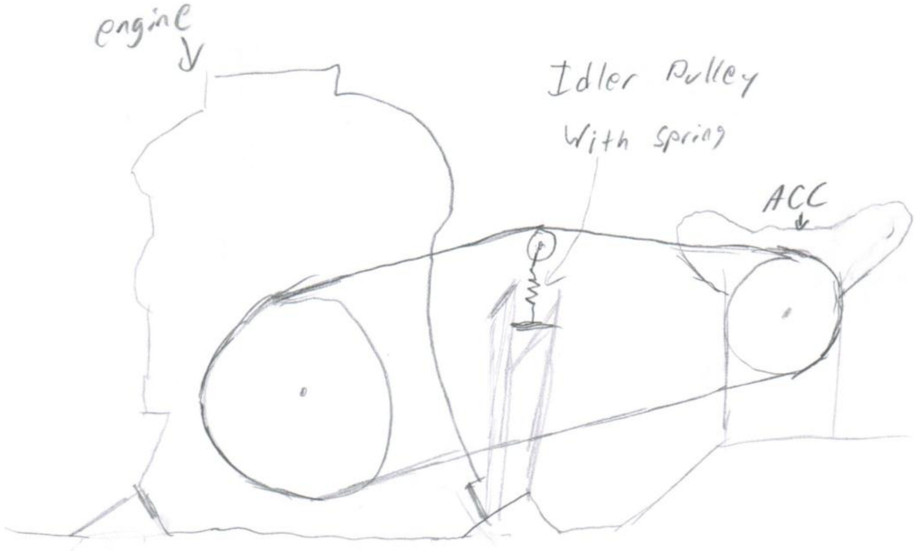
Shock Absorber Mounts

Not to scale



The shock absorber design is similar to the pivot mount except there are four shock absorbers, each one an equal distance from the center of gravity of the ACC, and there is no pivot mount. The shock absorbers would be placed between the mount plate and the frame.

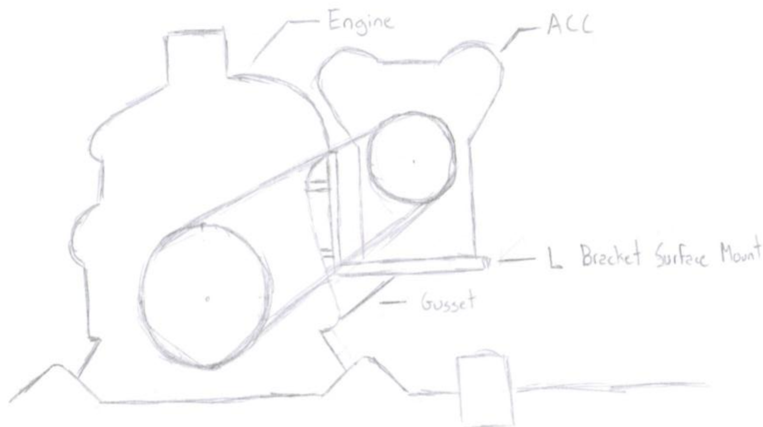
Idler Pulley to Reduce Belt Whip



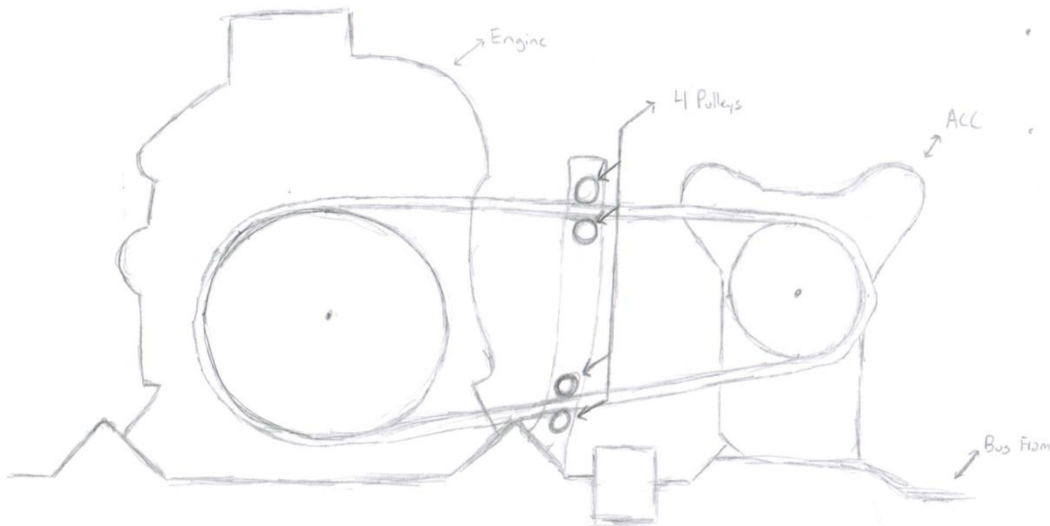
By attaching an idler pulley with spring, the tension in the belt can be increased. If a proper pulley/spring configuration is used, it could help to maintain a constant tension at all times to reduce belt whip.

Compressor Mounted to the Engine

- ACC mounted to engine using an L bracket
- L bracket is attached to the engine and supported by a gusset to minimize vibration
- Line of alignment is maintained between the crankshaft pulley and the ACC pulley



Guided Pulleys for Reducing Belt Whip



- Two pulleys used on top and bottom of belt loop
- Pulley spacing designed to restrict the vertical belt whip near the center of the belt loop
- Pulleys are attached to a bar that is mounted to the bus Frame

Addition of Damping Pulley

- Damping pulley attached to the crankshaft pulley
- Reduce belt whip due to engine vibration