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Development of a Hybrid Vehicle Powertrain Test Laboratory

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DEVELOPMENT OF A HYBRID VEHICLE POWERTRAIN TEST LABORATORY

By

BENNET SAMUEL SOUNDARRAJ

A Thesis Submitted to the College of Engineering Department of Mechanical
Engineering in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
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Development of a Hybrid Vehicle Powertrain Test Laboratory

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Bennet Samuel Soundarraj

This thesis was prepared under the direction of the candidate's Thesis Committee Chair, Dr. Marc Compere, Professor, Daytona Beach Campus, and Thesis Committee members Dr. Darris White, Professor, Daytona Beach Campus, and Dr. Charles Reinholtz, Professor, Daytona Beach Campus, and has been approved by the Thesis Committee. It was submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

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.

Abstract

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Title: Development of a Hybrid Vehicle Powertrain Test Laboratory

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During the last two years, Embry-Riddle Aeronautical University has installed and tested a fully functional eddy-current chassis dynamometer testing facility on campus. An automotive test facility requires a systems engineering approach to install, calibrate and commission a chassis dynamometer. This thesis shows that, the dynamometer test facility was successfully installed, commissioned and documented to safely support the power train development and testing. We can currently test the EcoCAR vehicle and a number of other front-wheel-drive vehicles at our university campus using the eddy current chassis dynamometer.

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Chapter I

INTRODUCTION

The thesis discusses and explains the various aspects of an automotive chassis dynamometer test system. The main crux of this thesis is to fulfill the requirement of Embry-Riddle Aeronautical University which needs an automotive chassis dynamometer. The design, installation, construction and commissioning of the chassis dynamometer services need to be installed in test facility, safety operating procedures and usage in automobile industry. Figure 1.1 shows the picture of a typical chassis dynamometer.

Figure 1.1: A Typical Chassis Dynamometer from Land and Sea

Dynamometers are used to provide performance data to builders and designers of a powerplant such as internal combustion engines, electrical motors, jet engines and others. It is a way to measure the power created by the powerplant. This is significant, because although a designer can predict the amount of power that a specific powerplant should be able to produce, in reality the theoretical and actual power produced by the powerplant is not equal.

These losses come from various places, for example friction and internal resistances [1]. Therefore the designer/builder finds the actual power produced by a powerplant by the use of a dynamometer test system. Figure 1.2 shows a transient engine dynamometer.

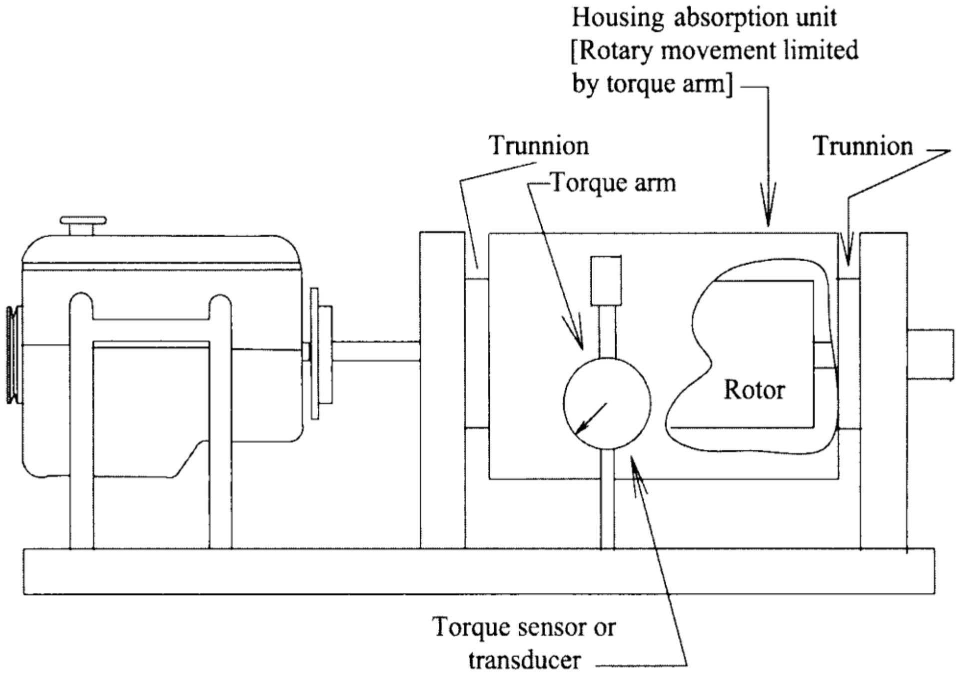


Figure 1.2: A Transient Engine Dynamometer [3]

A dynamometer is a mechanical device that places a resistance load to measure the resulting loaded speed of the powerplant to determine power output [2]. A dynamometer which is designed to be driven is called an absorption or passive dynamometer and the dynamometer that drives or absorbs is known as universal or active dynamometer. Dynamometers can measure powers ranging from 0.25watt electric motors to multi thousand pound thrust jet engines, but a different type of dynamometer will have to be installed for each specific powerplant. A challenging problem facing the engineer for all these is setting up the test facility for the dynamometer. In this thesis a powerplant dynamometer will not be installed, but rather a chassis dynamometer. A chassis dynamometer allows a complete vehicle power system to be exercised in a repeatable, highly instrumented laboratory environment.

Significance of the Study

A chassis dynamometer is mainly used in the automotive industries to measure the power that an automobile or other wheeled vehicle puts to the ground or to the tires. The power produced by an engine in an automobile does not directly go from the engine to the drive wheels, but instead the power goes through a drivetrain before reaching the tires or ground. A drivetrain is a section after the transmission which consists of the parts of the powertrain excluding the engine and transmission. Measuring the power at the tires gives the designers a better understanding of actual vehicle performance capabilities. Unlike an engine dynamometer, a chassis dynamometer includes the transmission and differential losses and gearing effects to help designers better understand the end power and torque capabilities of a vehicle. Therefore the designers can decide if the current engine, transmission, and differential configuration are suitable to achieve the desired vehicle performance.

One can find the power being transmitted to the ground by a vehicle, with a chassis dynamometer. Also, the efficiencies of the subsystems of the powertrain can be found with appropriate instrumentation of the test vehicle. Subsystems of a powertrain include the engine, transmission, and the differential. By knowing the losses in a powertrain, an estimated efficiency can be calculated to inform the designer on the amount of power likely to be lost, which helps the designers in selecting the appropriate subsystems for the powertrain to obtain the desired vehicle characteristic performance. In other words, a chassis dynamometer is more useful than a typical engine dynamometer, by its ability to test multiple configurations of powertrain subsystems as an entire powertrain system. Studies have shown that, chassis dynamometers have the ability to test an entire powertrain system with appropriate instrumentation. It allows the designers to study the individual subsystems of a powertrain to design a new vehicle in a better way [1].

Statement of the Problem

Testing the powertrain of a vehicle is a crucial part in researching and developing new designs for the automotive industry. In our case, it is important to further increase the university's research capabilities by developing automotive research facilities.

We have been testing our EcoCAR vehicle at the Daytona International Speedway, but a Chassis dynamometer allows us to do more extensive testing on the EcoCAR vehicle to study the experimental EcoCAR hybrid electric power system.

After testing of the EcoCAR, the chassis dynamometer will take an active role in developing future vehicles in our university. A chassis dynamometer system can be supplied in two fashions. The first choice is to design and build your own chassis dynamometer. The second choice is to purchase the chassis dynamometer system from a company that designs and builds chassis dynamometer systems, the decision was made to purchase a chassis dynamometer.

Purpose Statement

The purpose of this study is to install and commission a chassis dynamometer for automobile power system testing for front wheel drive vehicles at Embry-Riddle.

Limitations and Assumptions

Test limitations are primarily vehicle size and power train power rating. The EcoCAR laboratory has a limited vehicle bay with and requires a slight turn upon entering. The dyno is limited to [Hp rating] horsepower according to Land and Sea documentation.

The assumptions are adequate air flow entering and exiting the lab to dissipate heat generated. Also, the vehicle tie down points are assumed rigid and with adequate strength to retain the vehicle. The primary purpose of this Chassis dynamometer is to develop and test the EcoCAR2 hybrid electric vehicle power system.

Definitions of Terms

Absorbed Horsepower	Total horsepower absorbed by the absorption unit of the dynamometer and the friction components of the dynamometer
Actual Horsepower	It is the load horsepower that includes the friction in the dynamometer bearings and inertia simulation mechanism
Btu (British Thermal Unit)	The amount of energy or heat required to raise the temperature of one pound of water one degree Fahrenheit.
CFM (Cubic Feet per Minute)	A measure of volume flow rate, or air moving capability of an air moving device. Volume of air moved per minute [5]
Closed Loop Control System	A control system with a feedback loop that is active.
Dynamometer	An instrument, which measures the motor’s performance by creating a load
EcoCAR	The Next Challenge was a three year collegiate advanced vehicle technology engineering competition established by United States Department of Energy (DOE) and General Motors (GM), and was managed by Argonne National Laboratory.

Eddy Current	an electric current induced in a massive conductor, such as the core of an electromagnet, transformer, etc., by an alternating magnetic field.
Heat Load	The heat that the test vehicle and the dyno dissipates to the atmosphere.
Power Capacity	It is the number set by the manufacturer that is fundamental to the capacity of drive tires.
Roll Speed	It refers to the speed of the roll on the chassis dynamometer and can be directly related to the vehicle speed [2]
SP (Static Pressure)	A measure of the resistance to the movement of the forced air through a system or installation

List of acronyms

AAT	Ambient Air Temperature
ABC	Active Body Control
ABS	Antilock Braking System
AC	Alternating Current
ACC	Adaptive cruise control
ACC	Automatic Climate Control
Accel	Acceleration
A/C	Air Conditioning

ACT	Air Charge Temperature
AFR	Air to Fuel ratio
APP	Accelerator Pedal Position
ASCD	Auto Speed Control Device
A/T	Automatic Transmission
AWD	All Wheel Drive
BAP	Barometric Absolute Pressure
BHP	Brake Horse Power
BMEP	Brake Mean Effective Pressure
BP	Back Pressure
BPA	Brake Pedal Applied
CC	Cruise Control
CL	Closed Loop
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CS	Charging System
DC	Duty Cycle
ECU	Engine Control Unit
ERAU	Embry-Riddle Aeronautical University
ESO	Engine Shutoff
EST	Electronic Spark Timing
EV	Electric Vehicle
EXH	Exhaust
FWD	Front Wheel Drive
FUDC	Federal Urban Driving Cycle

FTP	Federal Test Procedure
G/sec	Grams per Second
HC	Hydrocarbons
HEV	Hybrid Electric Vehicle
Hp	Horsepower
HVIL	High Voltage Interlock Loop
IAT	Intake Air Temperature
IC	Ignition Control
IDS	Integrated Diagnostic Software
Km	Kilometer
KPa	Kilopascal
KS	Knock Sensor
KV	Kilovolts
MAP	Manifold Absolute Pressure
MPH	Miles per Hour
MV	Megavolt
mW	Millivolt
MVSA	Motor Vehicle Safety Act
MVSS	Motor Vehicle Safety Standards
O2S	Oxygen Sensor
OBD	On Board Diagnostics
OD	Overdrive
ODO	Odometer
OL	Open Loop
RPM	Revolutions Per Minute

SPD	Speed
TAC	Throttle Actuator Control
TACH	Tachometer
TB	Throttle Body
TP	Throttle Position
UDDS	Urban Dynamometer Driving Schedule
USCAR	United States Council for Automotive Research
VAC	Volts Alternating Current
VDCS	Vehicle Dynamics Control System
VLCM	Variable Load Control Module
WOT	Wide Open Throttle

Review of Relevant Literature

Dynamometer Introduction

Since the invention of the Automobile, there has been a drastic change in the field of automobile testing. It helps in building technologies to ensure that the highest standards are met in terms of Product quality, reliability, durability and safety. An engineer has been under constant pressure either to increase engine power or to improve the fuel economy so he needed a way to test the power output and fuel economy of automobile engines and hence the dynamometer was invented.

The schematic diagram of Friction rope dynamometer is shown in figure 2.1. The dynamometer function is to impose variable loading conditions on the engine under test, across the range of engine speeds and durations, thereby enabling the accurate measurement of the torque and power output of the engine. William Froude is regarded as the father of the modern dynamometer [3]. Figure 1.3 shows the friction rope dynamometer.

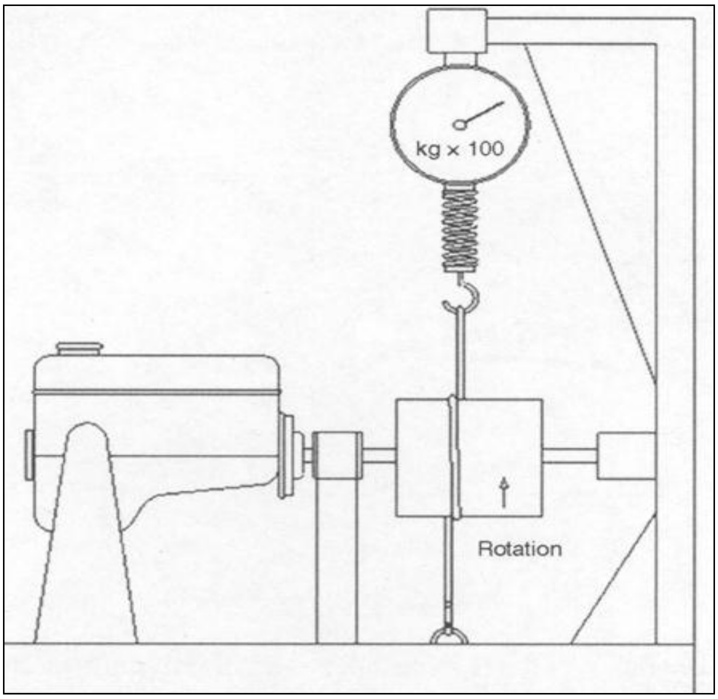


Figure 1.3: Friction Rope Dynamometer [3]

To understand the working principle of dynamometer, Imagine a spring balance is anchored to the ground with a rope attached to the top eye and wrapped around a drum with a slipknot. The slipknot is tightened as the drum rotates, the rope then will be tensioned, and the balance will extend to indicate this tension as the weight. Friction between the rope and the drum will slow the drum and its driving engine until balancing the weight. For example, at 1000 rev/min; the spring balance reads 210 Kg. In effect the weight being lifted is 210 kg, and the speed of the drum or the engine will then be used to find the horsepower. Likewise, the engine is clamped on a test bed frame, and the output from the engine flywheel is connected to a driveshaft and hence a dynamometer helps in reading the horsepower [3].

Dynamometer Mechanism

Figure 1.4 illustrates the operating principle of the dynamometer

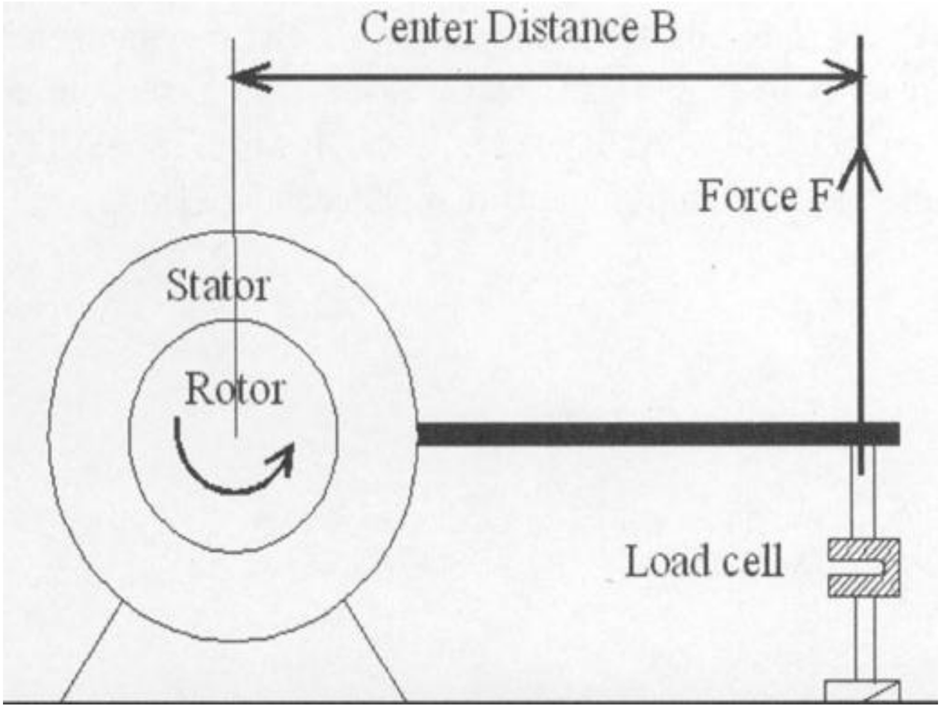


Figure1.4: Torque Measurement [3]

The rotor is coupled to the stator electromechanically, hydraulically or by mechanical friction. The stator is balanced with the static calibration. The torque exerted on the stator with the rotor turning is measured by balancing the stator with weights, springs, or pneumatic means.

If the torque generated by the engine is T [3], then

$$T = F\,b \qquad (1.1)$$

The power P delivered by the engine and absorbed the dynamometer is the product of the torque and the angular speed as

$$P = 2\pi NT \qquad (1.2)$$

Where N is the crankshaft rotational speed, In SI units,

$$P\ (KW) = 2\pi N\ (rev/sec) * T\ (Nm) \times 10^{3} \qquad (1.3)$$

In U.S. units

$$P\ (hp) = (N\ (rev/min) * T\ (lbf.ft)) / 5252 \qquad (1.4)$$

Dynamometer Choice

The most difficult question facing the engineer designing a test facility is the choice of most suitable dynamometer. Every dynamometer has it pros and cons. The earliest rope brake dynamometer is extremely dangerous. It is nevertheless capable of giving accurate measurements of power. Its successor, the Prony brake, also relied on the mechanical friction and like the rope brake required cooling by water introduced into the hollow brake drum and removed by a scoop. Both of these devices are only of historical interest. Their successors may be classified according to the means adopted for absorbing the mechanical power of the prime mover driving the dynamometer [8].

Types of Dynamometers

Dynamometers can be classified in many different ways based on absorption, motoring, or universal. The four types of dynamometers that are reasonable alternatives for our application are the electrical generator, the water brake dynamometer, the eddy current dynamometer and the inertia dynamometer. The reason that these four will be discussed is because they are the most common dynamometers in industry. They are by no means the only dynamometers used. In all cases the size of the dynamometer load system is dependent on the amount of power that needs to be dissipated. Although all four dynamometers power absorption capabilities can be increased to absorb larger amounts of power, the power absorption envelope characteristic is also important. The power absorption envelope tells how much power and torque can be absorbed at specific speeds [3].

Electrical Generator

Electrical generators in most cases are the same as electric motors. The only difference between the two is the way they are used. Figure1.5. shows an example of an electrical generator.

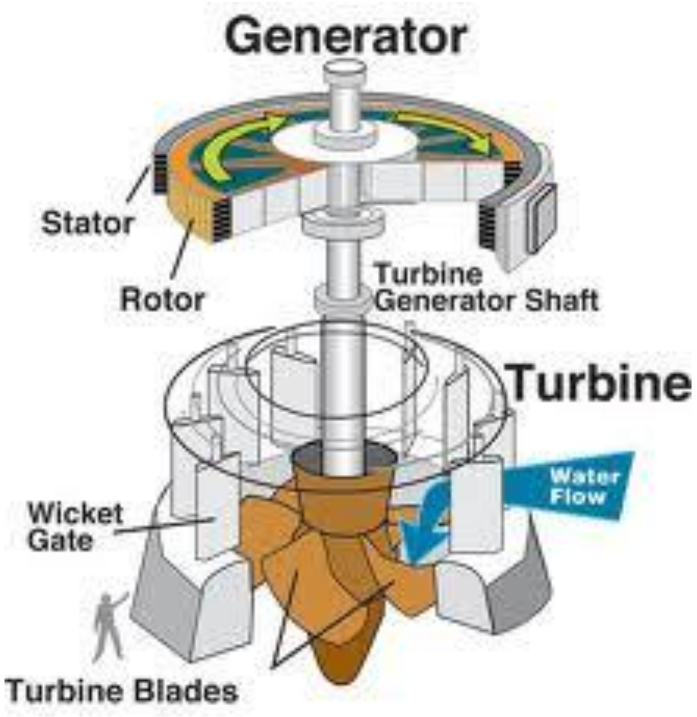


Figure 1.5: Electrical Generator (Hydro Power Generator)

In the case of an electrical motor, electrical power is supplied to the motor to produce mechanical work in the form of shaft work. An electric generator is like an electrical motor, except that instead of generating work it generates electrical power. In other words, the electric generator converts work done on the shaft to electrical power in the form of the voltage and current. The generated electrical power is dissipated mostly by running the electricity through a series of electrical resistors that dissipate the power as heat. Another way to remove generated electrical power is to send it back into the electrical grid [1].

The power can be calculated in two ways. The first method is to place the generator on trunion bearings, which will allow the generator to rotate around a defined axis. As the generator rotates around the axis an angular velocity of the load shaft (ω) and a reaction torque (τ) required to hold the generator in place can be measured. Once the angular speed and torque are measured then the power (P) that the generator produces will be known.

$$P = \tau \omega \tag{1.5}$$

To measure the torque, a moment arm of a known length is attached perpendicular to the generator. As the generator rotates it produces a force at the end of the moment arm, which can be measured by either strain gauges or a force transducer. The torque is then calculated by the following equation [1.6].

$$\tau = r F_m \tag{1.6}$$

F_m = force applied to the end of the moment arm

r =length of the moment arm

Equation 1.6 - 1.5 can be rewritten as

$$P = r \omega F_m \tag{1.7}$$

By using Ohm’s Law, the power produced by the generator can be measured by measuring the voltage and current of the electrical power produced by the generator. This is much simpler and more accurate than the first method. The torque is as important as the power for automobiles, because torque dictates the amount of acceleration a vehicle has and the amount of road load that a vehicle can overcome. Both methods for determining power can be performed to verify that the power being measured is correct.

There are numerous advantages to the use of electrical generators as load systems. Its advantages are easy to measure power, ability to control the dissipation of power quickly and accurately, not overly difficult to measure torque and speed compared to the other dynamometer systems on the market. One of the major disadvantages to the electrical generator is the price tag. Electrical generators become more expensive as larger power absorption requirements are needed [1].

Hydraulic Dynamometer (Water Brakes)

A water brake dynamometer is basically an inefficient pump that absorbs power by pumping a fluid. The power device is connected to the water brake shaft that is connected to an impeller. The impeller rotates and moves a fluid (water) that is supplied to the brake. Unlike a normal fluid pump, the fluid does not flow freely. Instead, it has to flow around stationary vanes. These stationary vanes impede the movement of the water making the pump inefficient enough to cause large power losses. The power being lost from stream is transferred back into the water in the form of heat. The water being used as the working fluid has to be cooled or discarded. The amount of fluid flow to the brake is controlled by a control valve which increases the potential of resistance load while preventing the water brake from overheating [12].

Measuring the power being absorbed by a water brake is done in the same fashion as shown in equations (1.5) to (1.7) for the electric generator. The water brake is mounted on trunion bearings and a moment arm is attached to measure the resistance force and resistance torque of the brake. If the angular velocity of the water brake load shaft is also measured, the power can be calculated by equations (1.5) to (1.7). The following figure 2.4 shows the Water Brake dynamometer.

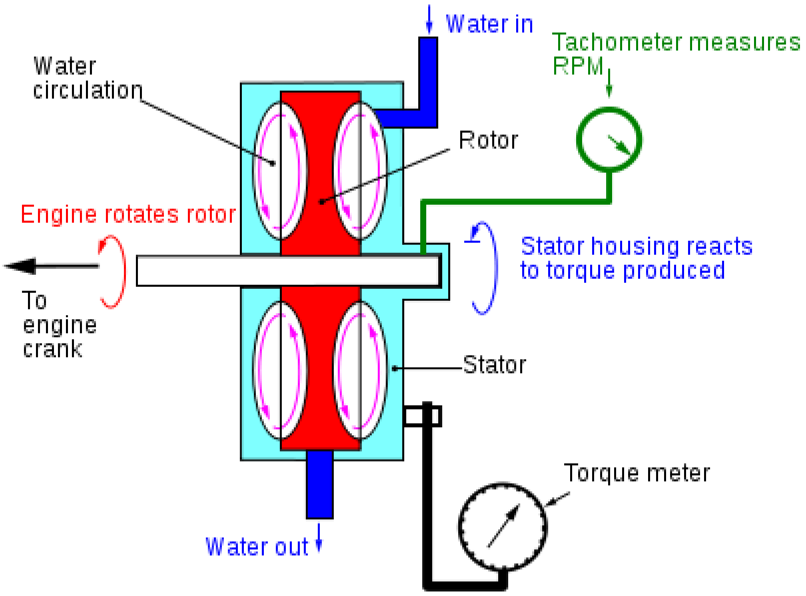


Figure 1.6: Water Brake Dynamometer for a Steam Turbine [7]

The advantages of a water brake dynamometer are numerous, but different from that of the electric generator. One of the advantages is that it is compact and relatively inexpensive. This is important due to the limited space and budget available for the project. One of the main drawbacks is its inability to absorb high amounts of power at relatively low speeds. Another drawback is controllability of the water brake. The less precise control of the amount of load causes higher uncertainty in the measurement of the power and torque. Also the need for a water system to keep the water brake cool and supplied with water is another disadvantage of the water brake [1].

Inertia Dynamometer

Unlike the water brake and electric generator dynamometer systems the inertia dynamometer has no active power absorption (brakes). Instead of using brakes to dissipate power, it uses the inertia mass to dissipate the energy. The following figure 2.5 shows the inertial dynamometer.

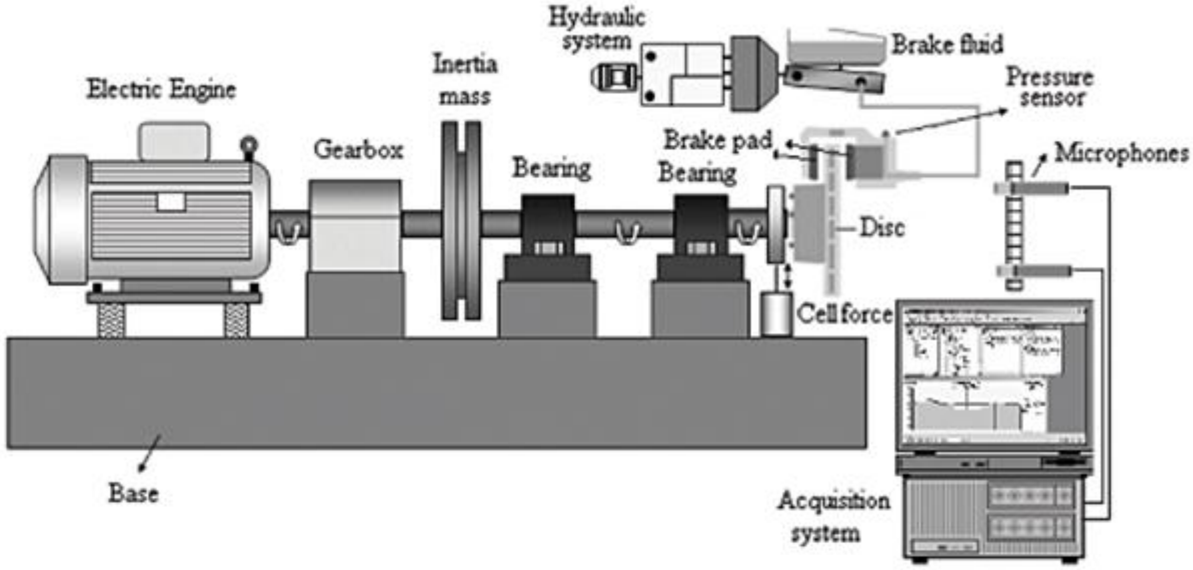


Figure 1.7: Components of an Inertial Dynamometer

The inertia dynamometer directly measures power and calculates torque, which is measured based on the acceleration of the inertia drums. It is this inertia that absorbs the power. It can be calculated or measured before the test. The power can be calculated from the following equations.

$$\tau = I\,\alpha \tag{1.8}$$

Where, I = Mass moment of inertia; α = Angular acceleration

When the work (W) done on the rollers is equal to the torque times degrees of rotation that the drum moved [1].

$$W = \tau\,\theta \tag{1.9}$$

Where $W_{d\,=}$ Work done on the drums; θ = Degrees the drum travelled

By combining these two equations we get

$$W = I\,\alpha\,\theta \tag{1.10}$$

Once the work is known, the power can be calculated by dividing work by time (t)

$$P = W/t \tag{1.11}$$

These equations help us calculating the power and torque of the vehicle. The primary advantage of the inertia dynamometer compared to the other system is a less expensive, self-contained system. Also it is very accurate and reliable. The first disadvantage is that you cannot connect directly to an engine or transmission easily. The second disadvantage is the need to continuously accelerate or decelerate to dissipate power from inertia only. This limits the duration of steady state power dissipation [1].

Eddy Current Dynamometer

An eddy current dynamometer works based on the principle of electromagnetic induction to develop torque and dissipate power. Similar to an electrical generator, except for the fact that it is designed to be very inefficient, so it converts electrical power to heat effectively rather than electrical power generation for delivery to a load. Eddy currents are purposefully produced between stationary magnets and the rotating toothed rotor. The production of eddy currents causes high inefficiency as a generator and dissipates power effectively.

The power is converted to heat and has to be carried away to keep the dynamometer cool. Measuring the mechanical power being absorbed by an eddy current dynamometer is done in the same fashion as in the other dynamometers, measuring reaction torque with the load cell and measuring speed. An eddy current dynamometer's load is not controlled by an electrical motor. However, it is still classified as an electrical dynamometer because it still utilizes electricity to control the operation. Figure 1.8 shows a picture of an eddy current dynamometer that uses a strain gage to measure load.

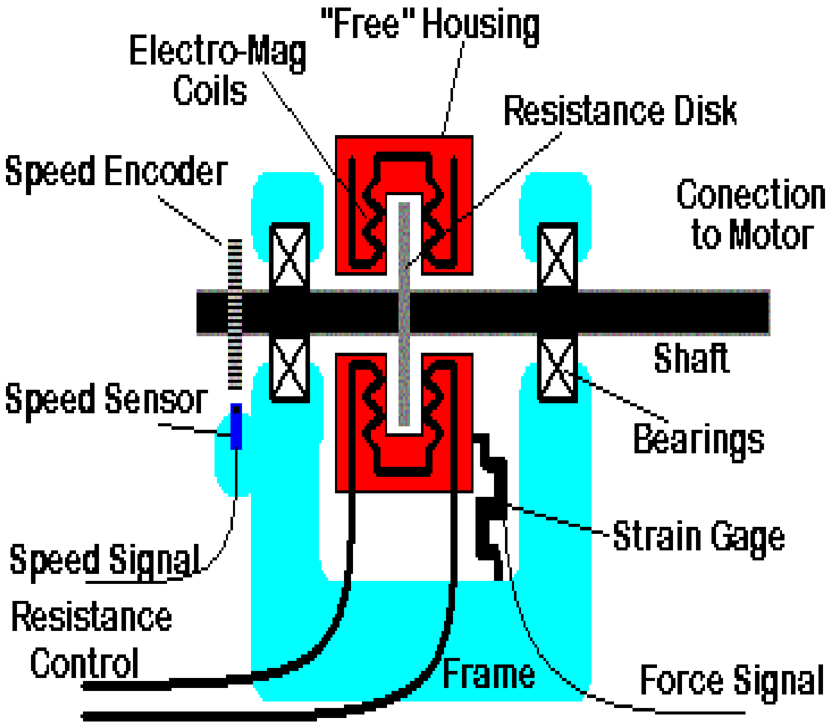


Figure 1.8: An Eddy Current Dynamometer.

There are two types of eddy current machines. The first is cooled by ambient air, while the other is cooled with a closed-loop water system. As expected the air-cooled system is much simpler to install and to maintain, as well as less expensive due to the extra equipment necessary to operate the water-cooled system. The air-cooled system is open to the atmosphere while the water-cooled system is encased similar to a water brake dynamometer.

The load on both types is controlled in the same manner, which makes use of the principle of electro-magnetic induction. A magnetic field that is parallel, but offset, to the axis of rotation is generated by a coil wrapped around a magnetic pole. These coils are stationary while one or two rotors, made of ferrous material, are rotated in close proximity of the coils. The rotor is attached permanently to the shaft that is connected to the power source.

When the coils are powered and the rotor is turning, circulating eddy currents and the dissipation of power in the form of electrical resistive losses occur. The circulating eddy currents generate power, i.e. heat, and as a result heats the rotors and surrounding air. The load is controlled by changing the current that is passed through the coils. Like the DC and

AC systems, the current is regulated with a control system that enables a response time to a 90% change in load that is 10 times faster than the water brake; however it is twice as slow as the DC machine, and 10 times slower than the AC machine.

The following figure 1.9 shows a cross section and end view of an eddy current dynamometer where 40 and 50 are the rotors, 60 is the coils of wire, and 200 is electromagnets running parallel to rotation.

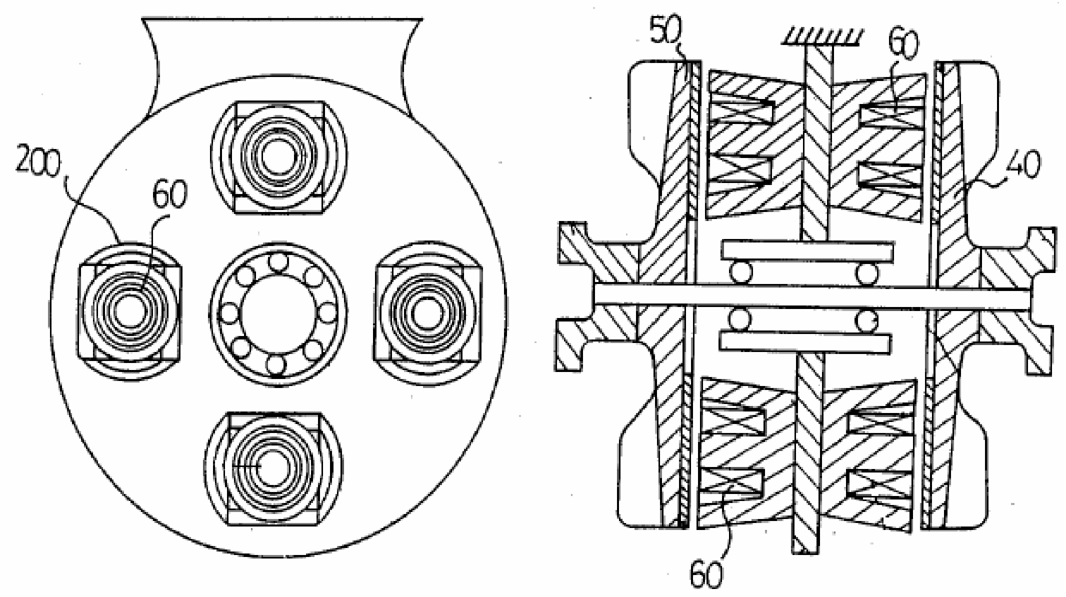


Figure 1.9: Eddy Current Dynamometer Cross Section and End View [6]

The eddy current machine is also capable of reaching a higher RPM and has a lower inertia compared to the other electrical dynamometers making it a more viable option for smaller displacement and horsepower applications that utilize a higher RPM range. It is also more affordable and smaller than the DC and AC dynamometers; however larger and more expensive than a water brake. Eddy current machines, like the water brakes, are not capable of acting as a starter for an engine; therefore an external starting source is necessary. The eddy current dynamometer is not capable of generating stall torque like the DC and AC machines, but it is significantly better than the water brake.

A typical eddy current’s performance curves are shown in Figure 1.10 with a corresponding description of each line segment in the following table

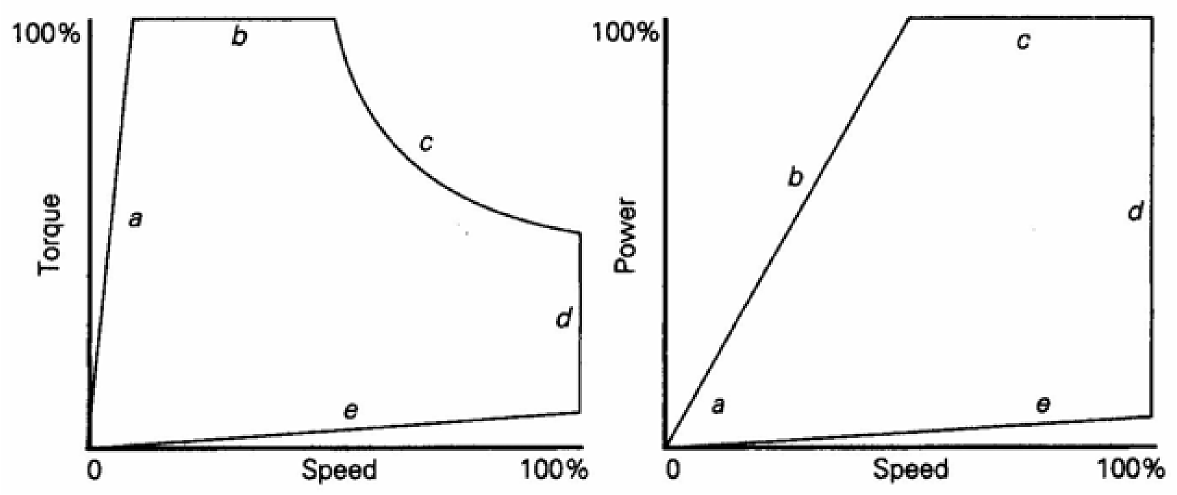


Figure 1.10: Performance Curves for Eddy Current Dynamometer [8]

Line Segment	Description
a	Low speed torque corresponding to maximum permitted excitation.
b	Performance limited by maximum permitted shaft torque.
c	Performance limited by maximum permitted power.
d	Maximum permitted speed.
e	Minimum torque corresponding to residual magnetization and friction.

Table 1.1: Eddy Current Performance Curve Segment Descriptions

The Eddy current dynamometer advantages include the ability to absorb high amounts of power at relatively low speeds, as required for our application. The eddy current dynamometer is also compact. Like the electric generator the eddy current dynamometer is very controllable, which reduces the uncertainty in the measurement of the power and torque.

Electrical dynamometers are much more expensive, when compared to a similarly horsepower rated water brake. The eddy current is the cheapest of the three available, while the AC and DC are similar in price. For an absorber that can withstand 200 horsepower, a water brake system costs nearly $4,700 [19], while the eddy current costs $12,950 [16], and the AC costs $49,950 [17]. A water brake system capable of absorbing 1,600 horsepower costs $14,450 [18], while an AC dynamometer capable of absorbing 1,250 horsepower costs $539,500. [17] The prices are for kits that include various necessary components and software that enable the dynamometer to operate.

There are also disadvantages associated with the eddy current dynamometer. The first disadvantage is cost; it is more expensive than a water brake but significantly less expensive than an electric generator for the same level of maximum power absorption. Another is that special care must be given to the elimination of vibration when using electric dynamometers because the sensitivity of the control will be affected [1].

Types of Tests and Purpose of Tests

As described in the previous section, there are different types of absorbers that can be used in the dynamometer system. Once the dynamometer has been selected, it can be attached to vehicle power system, so that the data can be collected about the engine. The tests being carried out in automobile industries are engine testing, transmission testing and vehicle drivetrain testing. These tests are usually motivated towards torque and power output based on the different engine speeds.

Engine Dynamometer Testing

Almost all measurements can be performed on highly dynamic engine test benches for both diesel and gasoline engines, from stationary to transient tests. The companies were interested in the amount of torque and power than an engine could produce and also the tests also being carried out to validate the components based on the engineer’s design and calibration. Automobile companies are spending large amount of money, manpower, time to get the expected results from the engine. A typical engine dynamometer testing is shown in Figure 1.11 below.

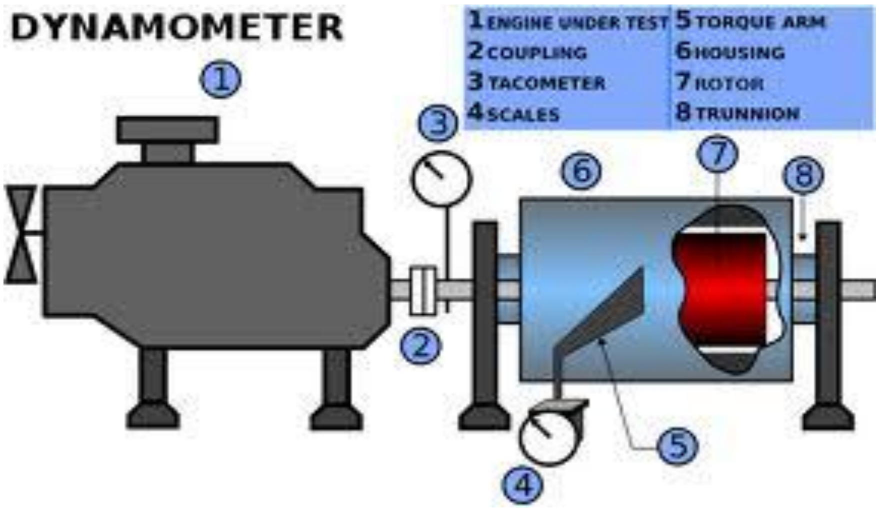


Figure 1.11: Engine Dynamometer Testing [7]

In an engine dynamometer, the engine is directly coupled to some kinds of power absorber. The tests are usually carried out based on the test schedule, which runs the engine at certain speed range and certain throttle positions. At every steps of speed change and throttle positions, the torque is recorded. The torque vs. speed plot is important for designers to look at the peak torque and horsepower at certain engine speed. It also helps further to calibrate the transmission.

Transmission Dynamometer Testing

A transmission dynamometer is the one which measures how much power is being transferred to the wheels. Transmission transfers the power from engine to wheels by reducing or increasing the torque based on the gear ratios. A transmission dynamometer tests the efficiency of the transmission in the way of getting more torque at a lower engine speed, fuel economy and shift quality [1].

Chassis Dynamometer Testing

A chassis dynamometer testing is the one that a complete vehicle will go through. It is the most important testing type because it will be the one which tells us about the actual capabilities of a vehicle after eliminating losses. The purpose of chassis dynamometer testing is to find the actual power and torque that a vehicle could achieve on the road [8]. The reason this is important that, once you know this information, a designer can accurately determine the amount of torque a vehicle has for pulling or towing and top speed of the vehicle. The designer knows this because what is placed to the wheels is all the power the vehicle has to use for propulsion. The Figure below is the elevation of chassis dynamometer

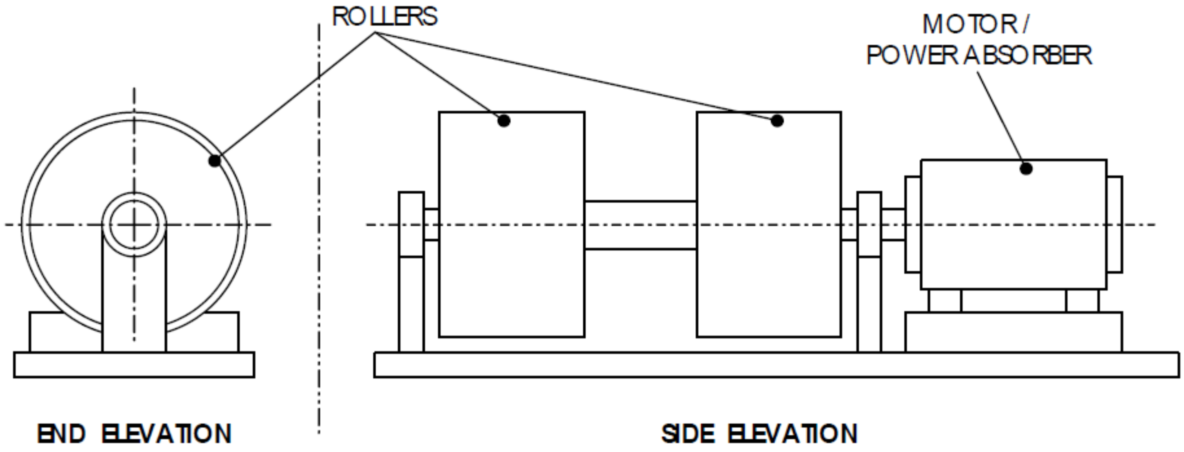


Figure 1.12: Chassis Dynamometer

The transmission and differential have more power losses than any other parts in the drivetrain. The output power is commonly absorbed by hydraulic or electric machines. The single unit can perform both monitoring (power output) and generating (power absorption) functions. Chassis dynamometers customarily incorporates many different measuring devices for conducting drive cycle and vehicle mapping tests, which are sampled and recorded by a computer controlled data acquisition system.

Summary

The primary purpose of a dynamometer is to absorb energy and characterize the power system in an instrumented environment. This energy is delivered in a rotational form and is transferred from the energy source using different types of mechanical system. To absorb energy, the rotation must have resistance. If instrumentation is utilized that measures the rotational speed (tachometer) and the resistance force (load cell) at a distance from the center of rotation, many parameters related to the energy source can be calculated. Revolutions per minute (RPM), torque, and horsepower are three significant parameters. The RPM can be determined directly from the tachometer and any relevant gear reductions. The torque can be determined by the load cell value and the distance from the center of rotation. The raw horsepower is linearly related to RPM and torque. To get comparative values of horsepower, corrections for temperature and humidity must be taken into account. Engine and chassis dynamometers are the most common types used today. An engine dynamometer is used to calibrate or test an internal combustion engine. A chassis dynamometer can be used in the same fashion; however it is capable of also testing driveline performance, mileage accumulation, and many other characteristics. This is the most popular use and will be the background for this thesis. The average person will never need to use or own a dynamometer. However, to any person or organization that is concerned with making modifications to their vehicle or engine in order to produce more power, a dynamometer provides a simple way to determine how the modifications improve performance. A simple test on a dynamometer before and after the modifications are made, will be able to answer that question. Engine dynamometers are not only useful for determining the benefit for upgrading engine components, but also for generating an entire timing and fuel map for the vehicle’s Engine Control Unit (ECU). Most engine dynamometers are capable of holding a motor at a certain speed, utilizing a feedback control process, while modifications are made to the ignition and fuel map to either produce a desired air-fuel-ratio (AFR) or to achieve the maximum amount of torque and horsepower. Original equipment manufacturers, race teams, and aftermarket manufactures specifically will conduct this type of tuning and testing on their engine systems on an engine dynamometer. As the name implies, an engine dynamometer is used to tune just the engine, no transmission or other driveline components are used, meaning the parasitic losses are at a minimum. Once an ignition and fuel map are generated and the motor is installed into the automobile, a chassis dynamometer can be used to determine many other parameters: efficiency of the drive train system, estimated fuel economy, emissions, acceleration, and reliability to name a few. In chassis dynamometer, the output commonly absorbed by hydraulic or electric machines, Eddy current absorber will be a viable option because it has lower inertia and capable of reaching higher RPM than hydraulic absorber. The air cooled eddy current absorber is much simpler to install and maintain than water cooled one. So the air cooled eddy current chassis dynamometer is an important tool that can be used for many different types of applications related to the internal combustion engine. Without the use of eddy current chassis dynamometer, the advances in automobiles would not be as simple to test/verify the overall effect that an added component contributes.

Hypothesis

It is proposed that, adding a chassis dynamometer to ERAU’s automotive laboratory will increase safety and the effectiveness during hybrid powertrain development. It is also proposed that a chassis dynamometer can be commissioned to test all university front wheel drive vehicles after a drive run with a Ford Taurus.

Chapter II

Systems Engineering Approach

Systems engineering is an interdisciplinary field of engineering that focuses on how to design and manage complex engineering projects over their life cycles [21]. It effectively provides a framework in which an initial idea with certain requirements may be realized into a full system with all necessary elements integrated into a complete product or result [22]. In order to install and commission the eddy current chassis dynamometer, it's necessary for us to define the requirements. The dyno lab requirements are listed below:

1.0 Embry-Riddle Aeronautical University - Dyno Lab Requirements
  1.1 Dynamometer acquisition
    1.1.1 The dynamometer system shall simulate road loading on the entire powertrain
    1.1.2 The dynamometer lab shall remain within budget constraints
    1.1.3 The dynamometer shall be low maintenance, reliable, and be operated by local trained personnel while ensuring safety of all staff, students, and faculty
  1.2 Chassis bay design
    1.2.1 The chassis bay design shall facilitate testing of all university front-wheel drive vehicles.
    1.2.2 The vehicle shall be properly positioned (front side shall face the garage door)
    1.2.3 Adequate ventilation shall be provided inside the chassis dynamometer bay.
      1.2.3.1 Supply and exhaust fan selection shall be based on air flow rate.
    1.2.4 Space shall be provided for supply and exhaust fans in the dynamometer pit.
    1.2.5 Adequate bumper clearance shall be provided for the longest vehicle to be tested.
    1.2.6 Deck plate shall be secured to the dyno frame and also, anchored to the concrete floor.

- 1.2.7 The dyno roller shall be centrally positioned based on the car lift in the back and the garage door in the front side of the car.
- 1.2.8 Provision shall be made to keep the garage door shut while testing the car.

1.3 Design and Fabrication

- 1.3.1 The grates shall provide passage over the obstacle and to add safety to fans.
- 1.3.2 The roller safety guard shall provide safety for lab personnel during testing.
- 1.3.3 The exhaust system shall evacuate the exhaust fumes coming out of the engine.
- 1.3.4 Adequate vehicle cooling shall be provided for engine, radiator, exhaust and underbody to prevent excess heating.

1.4 Construction

- 1.4.1 The construction company shall excavate and construct the chassis dyno pit.
  - 1.4.1.1 The company shall construct a flat and level pit floor under roller assembly.
  - 1.4.1.2 The pit walls shall blend with the existing concrete flooring in the lab.
  - 1.4.1.3 The construction company shall provide conduit for power and instrumentation wiring separately.
  - 1.4.1.4 The edge flange of the concrete shall be 1/2" to support the deck plate on top of the dyno steel frame.
  - 1.4.1.5 The concrete pit’s dimensional tolerance shall be no more than .25".

1.5 Installation

- 1.5.1 The construction company shall install the eddy current chassis dynamometer.
  - 1.5.1.1 The eddy current chassis dynamometer shall exactly be setup inside the custom cast concrete pit.
  - 1.5.1.2 The deck plate shall be secured on top of the frame and the concrete floor.
  - 1.5.1.3 The supply and exhaust fans shall be installed inside the chassis bay.

1.5.1.4 The power supply/control module shall be installed on the wall near the chassis bay.

1.5.1.5 The air brake palm button shall be installed near the eddy current power supply/control module.

1.5.1.6 Pressure regulator (maintain 90 psi) shall be installed for the air brake

1.5.2 The floor anchors shall be installed in the concrete.

1.5.2.1 The floor anchor locations shall be chosen to fit within the bay, be easily reachable during installation, and meet all strap maximum working load limits (WLLs)

DFMEA

Failure modes for safety-critical eddy current chassis dynamometer testing laboratory were listed and assigned severity, occurrence, and detectability values. Each of these was rated from 1-10, 10 being a high risk. The failure modes are ranked based on their criticality and risk priority number. Criticality was determined based on the severity and the occurrence. Risk priority number is calculated using equation.

$$\text{RPN} = \text{Severity} * \text{Occurrence} * \text{Detection} \tag{2.1}$$

The most critical failure modes are summarized in the table below:

DFMEA Analysis for Laboratory Dynamometer Capability

Item or Function	Potential Failure Mode	Potential Effects	Severity	Potential Causes	Occurrence	Current Process Controls		Detection	Risk Priority Number
						Prevention	Detection		
Vehicle under test	Person comes into contact with roller while vehicle at significant speed	Injury to the person	10	Vehicle steering system failure	6	Take appropriate precautions and follow SOP	Be aware of surroundings and steer people away (especially from the car front)	8	480

Vehicle under test	Vehicle tie downs break	Loss of vehicle control, incorrect data	9	Vehicle steering system failure	6	Follow SOP, ensure pre-test vehicle and dyno inspection	Monitor longitudinal /transverse movement	8	432
Vehicle under test	Floor anchors break	Loss of vehicle control, incorrect data	9	Vehicle steering system failure	5	Follow SOP, ensure pre-test vehicle and dyno inspection	Monitor longitudinal /transverse movement	8	360
Dyno controls	Feedback control failure	Could not hold engine RPM	8	Damage to servo control harness or sensor	7	Monitor DYNOMAX software errors	No RPM feedback	5	280
Vehicle under test	Parking on roller not proper	Loss of vehicle control, incorrect data	10	Driver not paying attention	5	Follow SOP	Monitor longitudinal /transverse movement	5	250
Vehicle under test	Drive shaft break	Loss of vehicle control, incorrect data	8	Aggressive testing	3	Follow SOP and ensure pre-test vehicle and dyno inspection	Monitor longitudinal /transverse movement	10	240
Vehicle under test	Tie downs - not properly installed	Loss of vehicle control, incorrect data	9	Vehicle control failure	5	Follow SOP	Monitor longitudinal /transverse movement	5	225
Vehicle under test	Vehicle steered off the roller	Loss of vehicle control, incorrect data	10	Driver not paying attention, vehicle steering system failure	4	Follow SOP	Monitor longitudinal /transverse movement	5	200
Dyno and pit area	Main shaft failure	Loss of vehicle control, incorrect data	10	Above max load carrying capacity	2	Avoid additional weight that would result in increased inertia	Monitor longitudinal /transverse movement	9	180
Dyno controls	Power supply failure	Damage to eddy current absorber	9	Forgot to bring voltage down after test, fuse blown, unplugged, wire damage	5	Monitor DYNOMAX software	No load, make sure the module is getting power	4	180

Dyno Controls	Control module failure	Damage to eddy current absorber	9	Forgot to bring voltage down after test, fuse blown, unplugged, wire damage	5	Monitor DYNOMAX software	make sure the load is under control	4	180
Dyno and pit area	Belt drive failure	Loss of vehicle control, incorrect data	9	Absorber overheating	5	Inspect belt for wear, damage. Replace as needed	Torque drops down suddenly	4	180
Dyno and pit area	Roller trunion failure	Loss of vehicle control, incorrect data	9	Above max load carrying capacity	2	Avoid additional load	Monitor longitudinal /transverse movement	8	144
Dyno and pit area	Debris falls into fan	Fan blade break	3	Separate room space, duct work	7	Maintenance work	Visual inspection	6	126
Dyno and pit area	Inlet fan failure	Dyno overtemp	8	Excessive use, power failure	4	Follow SOP	monitor dyno pit temp	3	96
Dyno and pit area	Exhaust fan failure	Dyno overtemp	8	Excessive use, power failure	4	Follow SOP	monitor dyno pit temp	3	96
Dyno and pit area	Exhaust blower fan fails/unplugged	Exhaust gas leakage in room	8	Excessive use, over temp	4	Follow SOP	Incorrect data points	3	96
Dyno and pit area	Absorber trunion failure	Loss of vehicle control, incorrect data	5	Above max load carrying capacity	2	Avoid additional load	Monitor longitudinal /transverse movement	8	80
Vehicle under test	Tire inflation	incorrect data	6	Overheating, old tires	6	Pre-test tire inflation check in SOP	increase in size	2	72
Dyno and pit area	Radiator fan failure	Engine over temp, incorrect data	5	Excessive use, power failure	4	Follow SOP	Incorrect data points	3	60
Vehicle under test	Tire shredding	Incorrect data	5	Overheating, old tires	5	Delay testing for tire cool down period	Pieces of tires on floor	2	50
DYNOMAX software	No data Input/ output	Test fail	7	software crashed, lost communication	7	Check data computer power supply	Flash light off	1	49
DYNOmite computer	Adapter port setup failure	No data transfer	5	port setup improper, damaged cable	7	Check the connections	Flash light off	1	35

Dyno and pit area	Dyno concrete anchors break	Change in dynamometer position	6	Aggressive testing, poor anchor design	2	Roller misalignment, follow SOP	Dyno vibration	2	24
DYNOmite computer	Adapter power supply failure	No data transfer	2	Adapter unplugged, failure	3	Follow safety precautions for adapters	Flash light off	1	6

Table 2.1: DFMEA Analysis for Laboratory Dynamometer Capability

A test must be stopped under different levels of urgency;

1. There is a safety violation and a person is in direct danger from the spinning roller
2. The vehicle under test fails
3. Dyno related hardware failure
4. The sensing or data logging fails

Three remedial actions with different urgency levels for stopping the test are:

1. Stop powering the vehicle and wait for the roller to come to a complete stop
2. Apply vehicle brakes to stop roller in a quick, but controlled manner
3. Apply dyno air brakes immediately along with vehicle brakes

On completion of requirements definition and DFMEA, the design work was started

Chapter III

Installation

The installation of the chassis dynamometer has been a multi-year project. It has been done in four steps involved dyno acquisition, design, construction and installation. The installation of chassis dynamometer has changed a lot from its original conception to what exists today. The reason for the changes has come from the needs and requirements of the dynamometer.

Dyno Acquisition

Eddy Current Chassis Dynamometer

Eddy Current absorbers are currently the most common absorbers used in modern chassis dynamometers. These eddy current chassis dynamometers is a kind of brake dynamometer used to simulate road loading on full powertrain and measures the vehicles ability to move or hold the RPM as related to the "braking force" applied.

It is necessary to keep the eddy current absorber cold. It can be either air cooled or water cooled. An air-cooled eddy current absorber is usually the most cost effective electric absorber to buy because their self-cooled rotors require no external water supply or resistor banks. It also eliminates water from the test cell and greatly reduces the maintenance burdens [20]. These air-cooled eddy-current capacities are RPM and rotor-temperature dependent. The initial cold torque and Hp limits are approximately twice their hot ones. The figure 3.1 illustrates the load chart of our air cooled eddy current absorber.

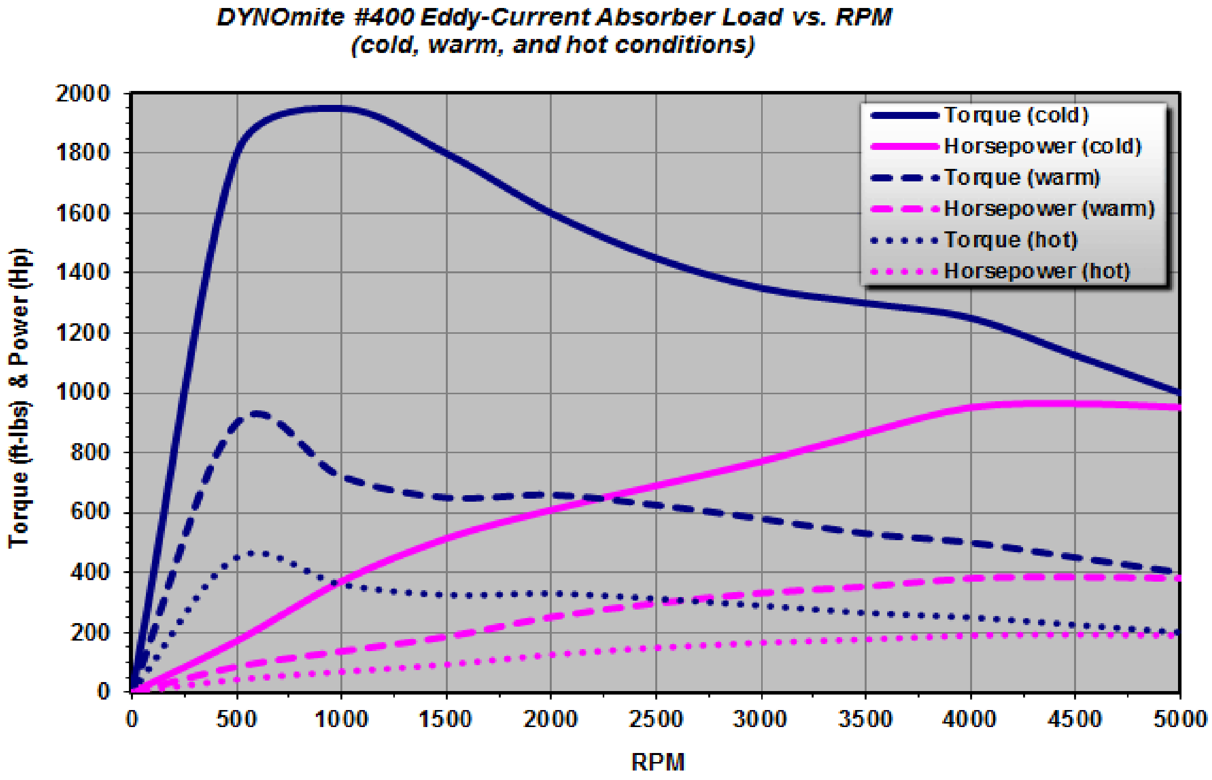


Figure 3.1: Load Chart – Eddy Current Absorber [11]

The eddy current chassis dynamometer is usually connected to a computer that records applied braking torque and calculates engine power output based on information from a "load cell" or "strain gauge" and a speed sensor. It can also be used as an inertia dynamometer which provides a fixed inertial mass load, calculates the power required to accelerate that fixed and known mass, and uses a computer to record RPM and acceleration rate to calculate torque. The tests are usually started from somewhat above idle to its maximum RPM and the output is measured and plotted on a graph [7]. Table below shows specifications of Land and Sea eddy current chassis dynamometer.

Dynamometer specifications

Model	3000 2WD eddy current chassis dynamometer
Brake Type	Air brake
Absorber	Eddy-Current (KR 250C PAU)
SAE(contact-patch ratio) Hp capacity	1350 Hp (1000/1.5"deform*µ*2wd)
Dyno speedometer	10 – 200 mph
MPH Range (tire-deformation method)	10 – 137 MPH (186sr/1.5"^.5deform)
Load control	Electronic auto-load control
Roller frame	96" wide (traction grooves on surface)
Axle weight capacity	10,000 lbs. (per axle)
Approximate dimensions	112"Width X 38"length X 30" height
Weight	4800 lbs.

Table 3.1: Dynamometer specifications

Where $\mu = 1$ (coefficient of friction for typical 24" diameter rubber tire on grooved steel roll),
sr = Tire’s speed rating,
deform = roll diameter induced tire deformation.

Eddy Current Absorber – KR 250C PAU

Eddy Current Absorbers offer very quick load control, moderate inertia, and high specific load capacity, especially in the lower RPM working ranges of most industrial-type engines. An air-cooled eddy-current absorber is the most cost-effective electric absorber which came along with the chassis dynamometer. Figure 3.2 illustrates the absorber unit used in the chassis dynamometer [15].

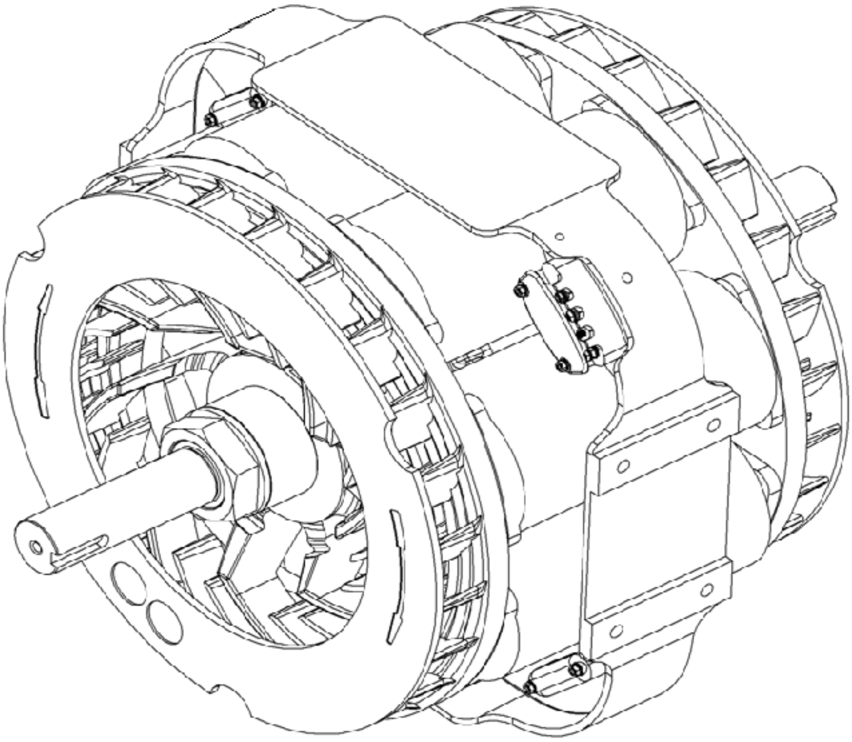


Figure 3.2: KLAM KR 250C PAU Eddy Current Absorber

The technical specifications of the eddy current absorber are listed in the table below.

Maximum braking torque		2970 Nm/ 2190 Lb-ft
Weight	Complete	422.5kg/ 931.44 Lb.
	Stator	328.5Kg/ 724.21 Lb.
	Rotors	94Kg/ 207.23 Lb.
Rotors Inertia		2.915Kgm^2/69.23 Lb-ft^2
Maximum Transmissible Torque		31600Nm/ 23305.75 Lb - ft
Maximum Admissible R.P.M (min^{-1}) Constant		4800
Maximum Admissible R.P.M (min^{-1}) Intermittent		5300
Air – Gap regulation (±0.1mm /± 0.0039 inch)		1.4mm / 0.0551 inch

Table 3.2: Eddy Current Absorber (KR250C PAU) specifications

The manufacturer's data sheet for this eddy current absorber can be found in Appendix D.

Modelling Eddy Current Chassis Dynamometer

The design has begun with the modeling of an eddy current chassis dynamometer in 3D software. The main purpose of modeling the dyno is

i. To locate the dyno inside the room based on the exact dyno dimensions.

ii. To predict the exact location of the dynamometer inside the pit

iii. To avoid complications during installation because the dyno weighs 4800lbs and requires heavy lift equipment.

iv. To understand how it works as a system and clearly communicate the intended operation with the vehicle inside the EcoCAR garage

v. To reduce the installation time, thereby reducing installation cost.

Based on the application and facility available, the three dimensional software CATIA V5 was used to design the dyno. An isometric view of the fully assembled eddy current chassis dynamometer is shown in figure 3.3

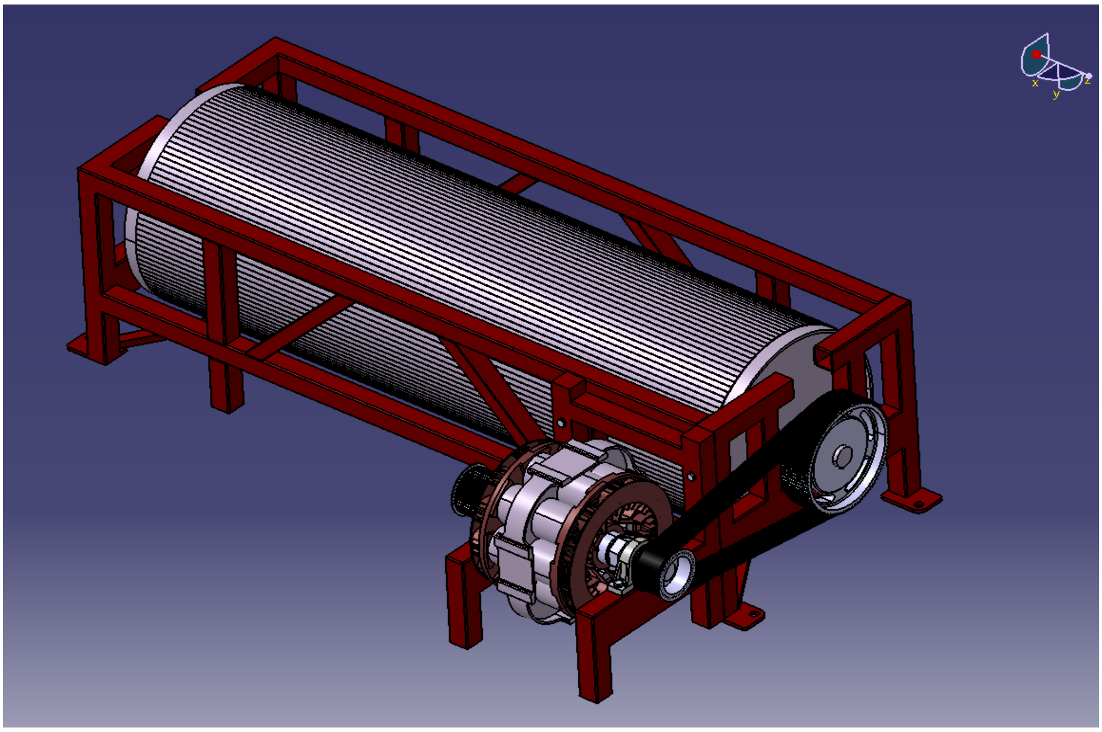


Figure 3.3: Three Dimensional Eddy Current Chassis Dynamometer

Inlet and Exhaust Fans

Ventilation is a common issue with an indoor test cell. Matching the effectiveness of even a mild outdoor breeze requires substantial fans. Considering this, it is required to provide huge fans for the air cooled eddy current chassis dynamometer. The initial idea from land and sea dyno of using tube axial fans with certain specifications for ventilation complicated the project by occupying more space, increasing in the cost of installation and fabrication and also the college of engineering decision to install the dyno inside the EcoCAR lab prompted the need for alternatives [13].

Determining Air Flow Rate in CFM

Air cooled eddy current absorbers usually radiate 100% of their absorbed engine power in to the test cell’s air. The room must be equipped with adequate high flow ventilation fans to remove this heat. For testing powerful engines, the required airflow is significant. Over 250,000 BTU’s per hour will be radiated for every 100 BHP being absorbed [9]. If the dynamometer will be performing short duty cycle tests, considerably less ventilation may be required.

After I analyzed various options, the HVAC supply and exhaust fans seemed promising. Once the fan type is known, the amount of air exchanged must be determined.

Chassis dyno test bays require enough airflow to avoid unsafe hot spots. Every design should consider the required information pertaining to the suggested air changes for proper ventilation. The specific ranges will adequately ventilate the corresponding areas in most cases. To determine the actual number needed within a range, if is good to consider the geographic location and average duty level of the area. For hot climates and heavier than normal area usage, select a lower number in the range to change the air more quickly. The CFM can be calculated as follows

$$\text{CFM} = (\text{Room Volume} / \text{Minutes Per Change}) \qquad (3.1)$$

$$\text{Room Volume} = (\text{Dyno Pit volume} + \text{Inlet fan room volume} + \text{Exhaust fan room volume}) \qquad (3.2)$$

$$\text{Volume} = \text{Length x Width x Height} \qquad (3.3)$$

Note: The supply and exhaust rooms are the same size, so the equation 3.2 becomes

$$\text{Room Volume} = \text{Dyno Pit volume} + ((\text{fan room volume}) \text{ x } 2) \qquad (3.4)$$

Substitute the values in equation 3.5, we get

$$\text{Room Volume} = (9.833' \text{ x } 5.667' \text{ x } 2.583') + ((3.250' \text{ x } 2.333' \text{ x } 2.583')\ 2) \qquad (3.5)$$

$$\text{Room Volume} = 143.934 + 39.170$$

$$\text{Room Volume} = 183.104 \text{ ft}^3 \qquad (3.6)$$

Assume if we change the air every 2 seconds of a minute, then the equation 3.1 gives

$$\text{CFM} = 183.104 / (2/60)$$

$$\text{CFM} = 5493.117 \text{ ft}^3/\text{min} \qquad (3.7)$$

Based on the CFM rating and application, figure 3.4 and table 3.3 show the chosen inlet fan and the dimensions that meet the required CFM in equation 3.7 and above the Fan’s CFM (Grainger # 7F957 – 5298 ft^3) recommended by the Land and sea Dynamometers.

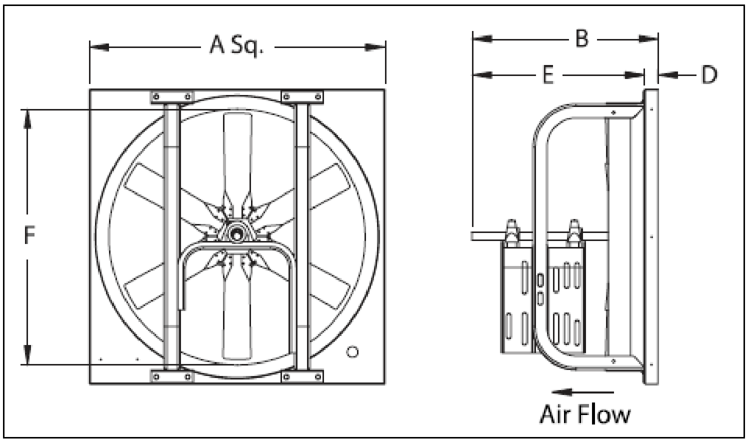


Figure 3.4: Supply Fan – Grainger Mfr. Model # 7CC08

Parameters	Dimensions
CFM	6175 ft^3
Height	28"
Width	28"
Overall Depth	18"
Maximum Depth	18"
Flange Width	1"

Table 3.3: Supply Fan Dimensions

It is necessary to provide same type of fan with same CFM on the opposite side of the wall for better air flow inside the dyno pit. So the exhaust fan was also chosen with the same specifications.

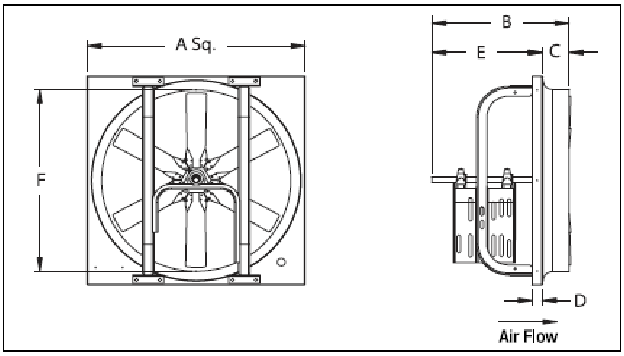


Figure 3.5: Exhaust Fan – Grainger Mfr. Model # 7CC79

Parameters	Dimensions
CFM	6175 ft^3
Height	28"
Width	28"
Overall Depth	18"
Maximum Depth	18"
Flange Width	1"

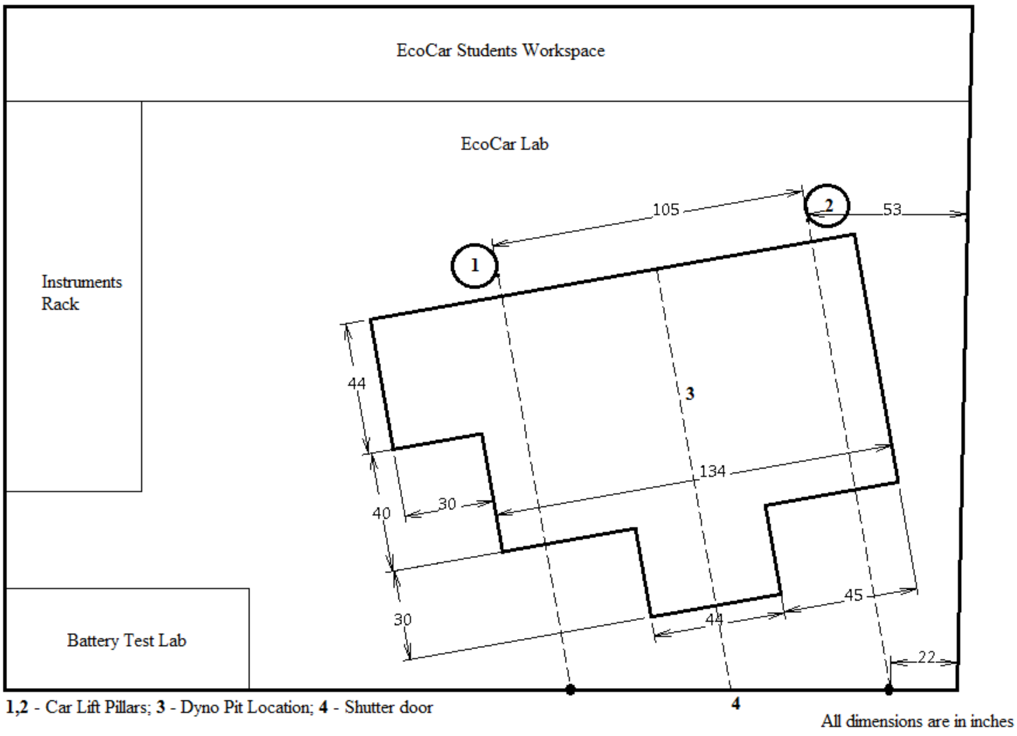
Table 3.4: Exhaust Fan Dimensions

Chassis Bay Design

Designing an engine dyno cell or chassis bay is a lot like laying out a new shop, there are no hard and fast rules. It is possible to spend just a little, or a small fortune, on both good and bad designs. It is necessary to have dimensioned pit drawing based on the design requirements listed in chapter II.

After the baseline design was completed, the dyno pit design was reviewed with Dr. Compere. We found some issues in providing ventilation for the dyno pit. The space needed for installing the supply fan was inadequate. So the design was changed to accommodate the supply fan.

After modifications, the Dyno pit is designed to accommodate both supply and exhaust fans and also it allows smooth in/out car movement. The Figures 3.6 shows a top view of the dyno location in the lab.



1,2 - Car Lift Pillars; **3** - Dyno Pit Location; **4** - Shutter door

All dimensions are in inches

Figure 3.6: EcoCAR Lab

Initially we decided to use both the steel angle and concrete lip to hold the deck plate. Later we decided to add an edge flange to improve strength and secure the deck plate with low cost. So we decided to add recessed edge supports on the inner edges of the concrete. Figure 3.7 shows the pit design

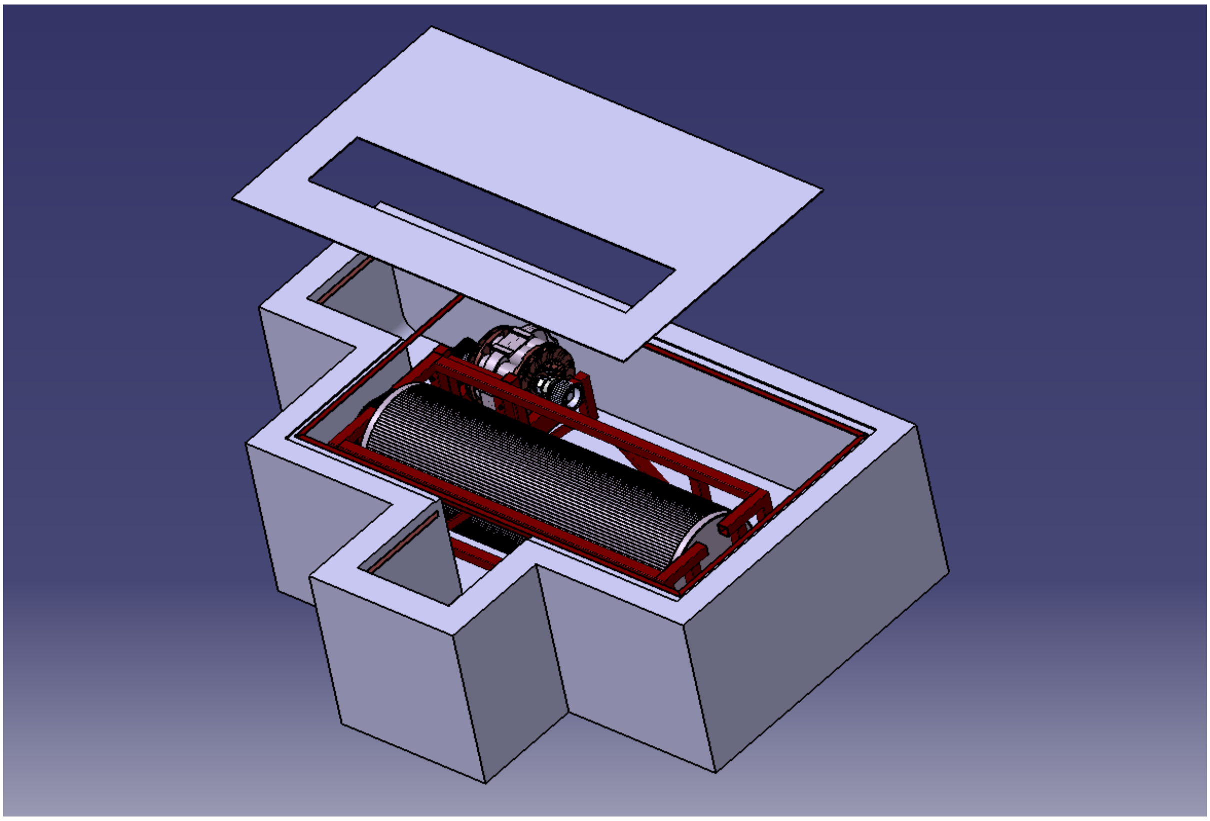


Figure 3.7: Dyno Pit Design

The grey outline in the figure is the eight inch concrete wall required to be built under the ground separately for the dyno.

Apart from construction, the wiring needed for the power supply and the data acquisition is minimal. So I decided to install the power supply/ controller module, data acquisition box and everything related to power supply next to the dyno. In addition, it was decided to construct three conduits separately inside the pit to take wires/hoses in and out of the pit used for absorber power supply, fan power supply, air brake and absorber RPM. Figure 3.8 below shows a three dimensional view of the Eddy current chassis dynamometer testing. Detail drawings are included in Appendix A.

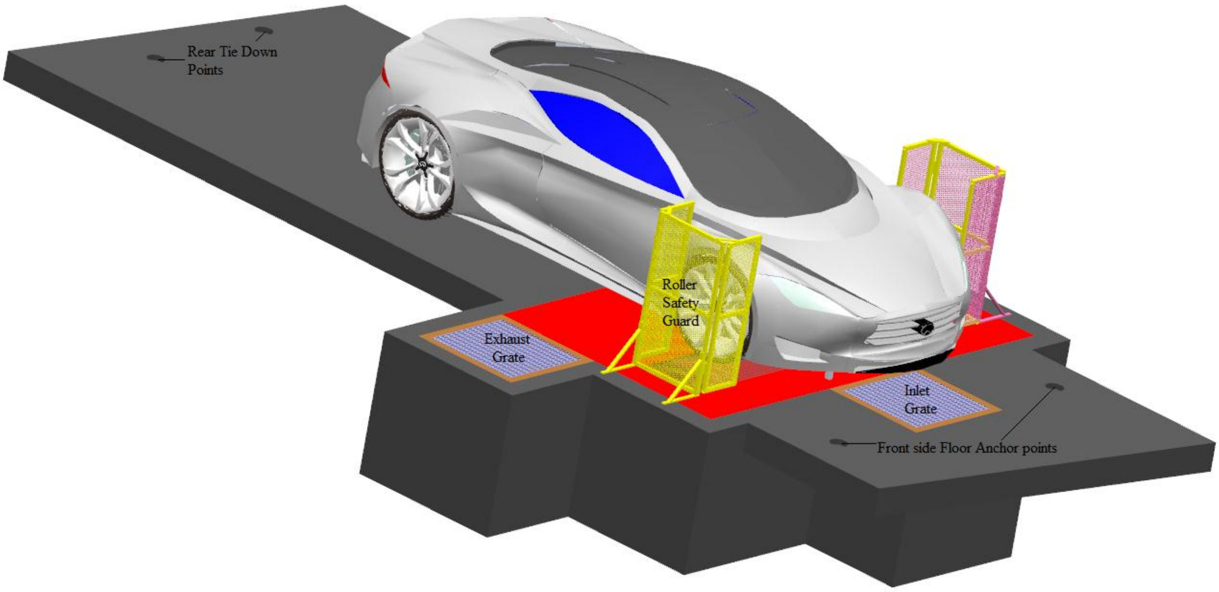


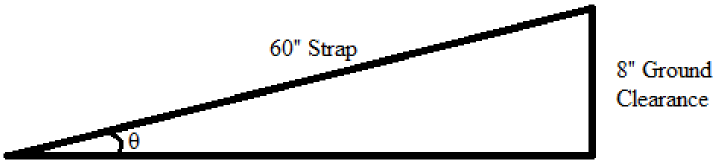
Figure 3.8: 3D - Eddy Current Chassis Dynamometer Testing

Floor Anchors and Vehicle Tie Downs

It is necessary to provide suitable vehicle restraint strap floor anchors. While there are many forms of restraining systems, we preferred heavy duty flush mount ‘D’ ring equipped plates. For concrete floors, it is necessary to secure each plate with two or three concrete anchors and several rings should be placed strategically in the test area.

The ratchet straps accomplish two goals. They provide a safety restraint for the car, by preventing it from driving off the chassis dynamometer and causing damage to the building or hurting individuals. It also provides sufficient downforce on the drive axle to prevent slippage between the wheel and the rollers. This is important, because if the wheels slip, the data is invalid. As the wheels slips, some power is being lost and is not transferred to the dynamometer.

The locations of this floor anchors were identified based on the 8" ground clearance of the car and the supplied 60" restraint strap, which should be installed less than 20 degrees with the ground to reduce the load on the anchoring hardware. The simple calculations below



$$\theta = \text{Sin}^{-1}(\text{Ground Clearance/ Strap Length})$$

$$\theta = \sin^{-1}(8/60)$$

$$\theta = 7.66 \text{ Degrees}$$

The circle indicated in figure 3.9 shows the location of the floor anchors based on these calculations.

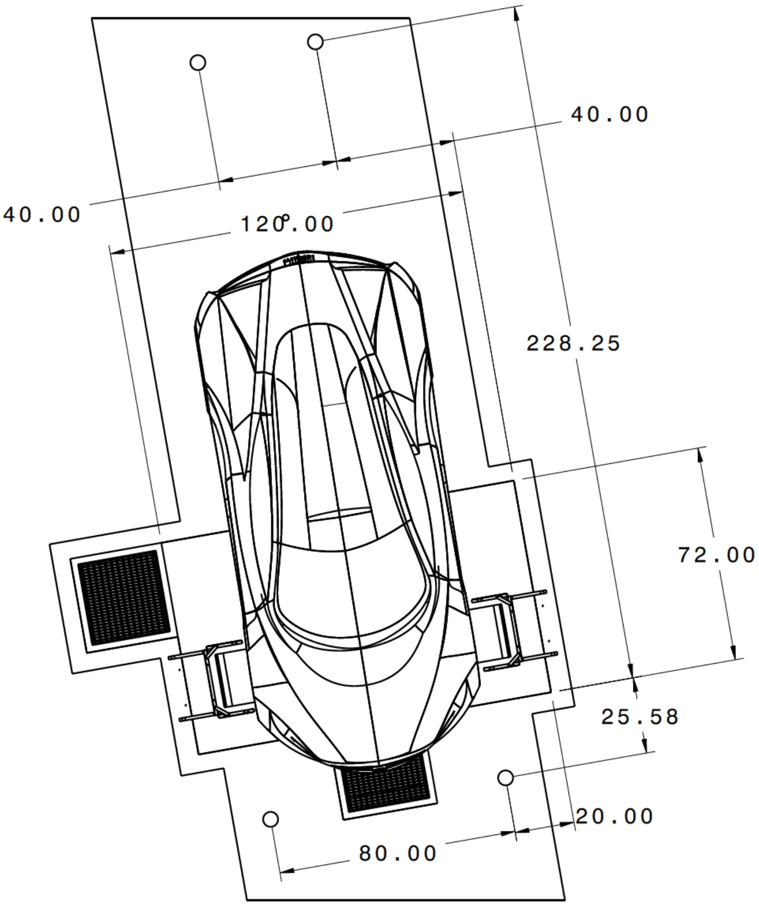


Figure 3.9: Floor Anchor Locations

It was found that the internal threaded drop in concrete anchor made of zinc plated steel is the right choice to install the flush mount ‘D’ ring equipped plates because it is easier to install. These anchor’s internal plug expands the anchor in four directions to hold it firmly inside the hole. To install, place the anchor in the hole, and insert the required installation tool into the anchor, and drive with a hammer until the thicker portion of the tool makes contact with the anchor. When installed, anchors sit flush with the surface. It is necessary to install The D ring equipped plates in both the front and aft directions of the car, as loads reverse during vehicle braking. Figure 3.10 shows the drop-in concrete anchor.

Fig 3.10: Drop-in Concrete Anchor

Steel Grates

Grate design considerations include cost, supported weight, accessibility and weather conditions. The grates designed here are to provide passage over the supply and exhaust fans and to add safety to fans. The size of grates on top of the supply fan and exhaust fan are the same size. Welded steel bar grate is extremely strong and durable for all load bearing applications and is primarily used for pedestrians. Figure 3.11 show the grate design for both supply and exhaust fan.

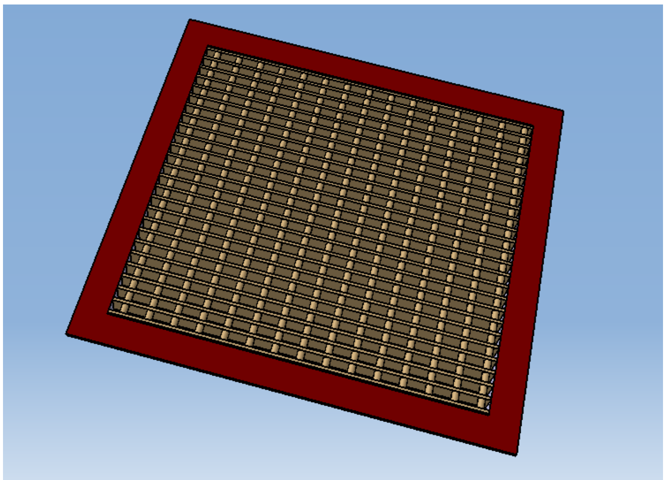


Figure 3.11: Steel Grate

Roller Safety Guard

Guards are used to keep the people from having direct contact with the machines. Guards may be in the form of sheet, woven or expanded mesh steel. In our case, expanded mesh steel was selected to keep students away from the dyno rollers while testing. Figure 3.12 shows the design of the dyno roller safety guard.

Figure 3.12: Roller Safety Guard

This fixed frame was designed in the form of butterfly wings to avoid stepping into the roller from all sides. In addition, it is also designed wing nuts, so that it will be portable.

Dyno Pit Construction

Once the design was finished, the dyno pit outline was marked on the floor with blue tape based on the dimensions provided in figure 3.6 to denote the exact location of the dyno pit. Figure 3.13 shows the dyno pit outline marked on the floor prior to construction.

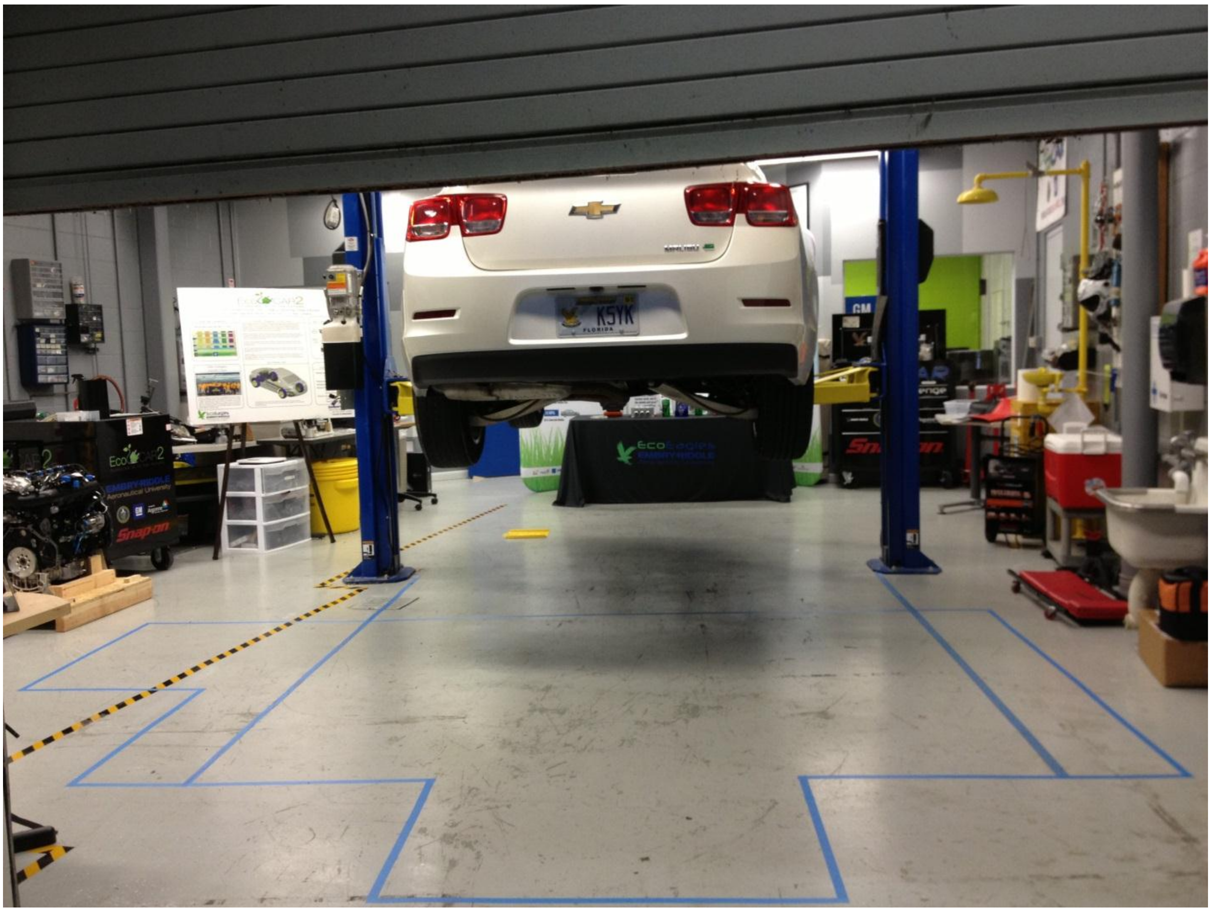


Figure 3.13: Dyno Pit Outline

For this in-ground chassis dyno roller system, a professional excavation and concrete work construction Company was contracted. The design plan and construction requirements were given to AM WEIGEL CONSTRUCTION INC. A quote was requested for the overall cost, which included design and building permit allowance, cutting, patching, concrete, termite treatment, caulking and coatings, electrical, dyno moving cost, insurance and other considerations. It was necessary to provide guidelines to the construction firm based on the construction requirements on chapter II. These kinds of projects require considerable foresight to make sure that the job will run smoothly. It is also necessary to provide exact dimensions of the Dyno pit. Figure 3.14 shows the dimensions of chassis dynamometer pit.

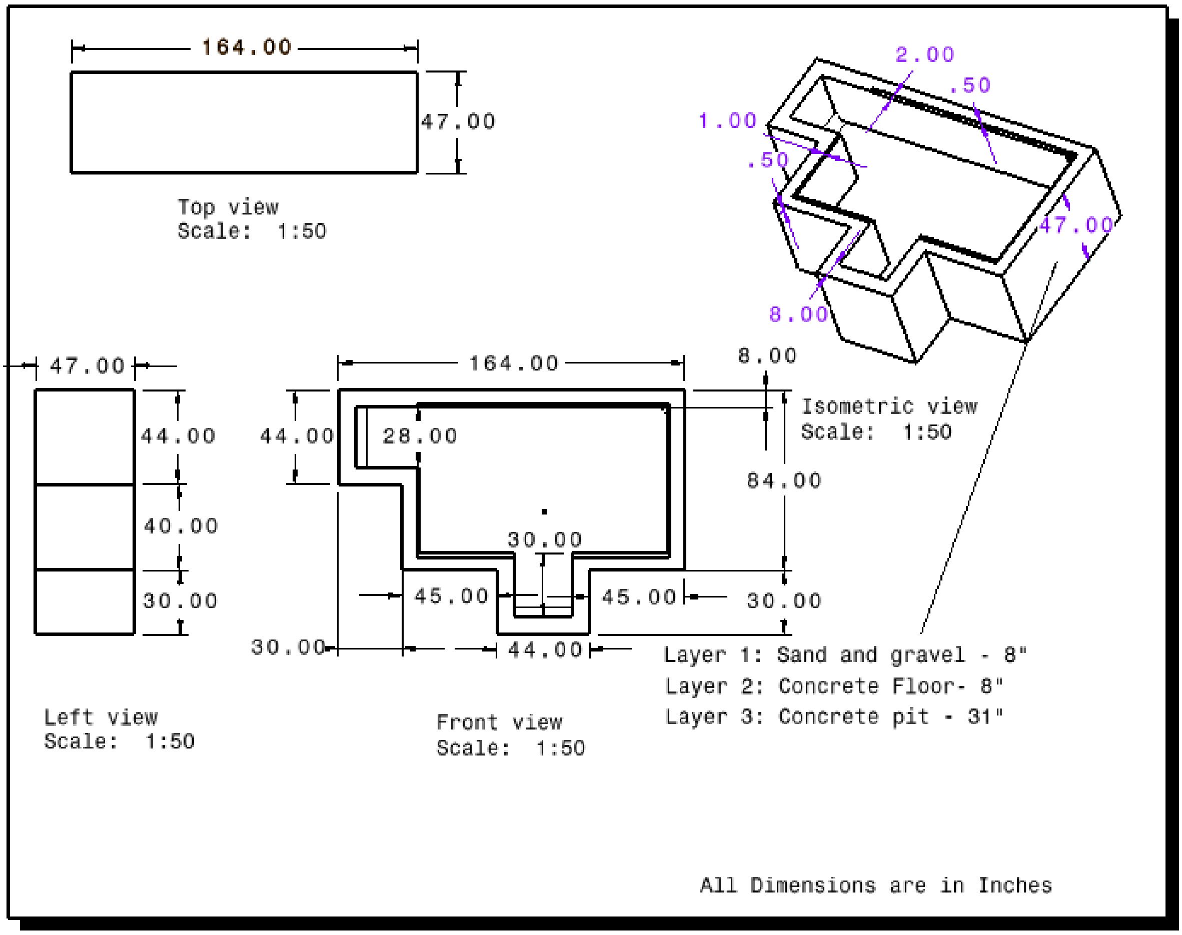


Figure 3.14: Pit Dimensions

The quote was sent to the college administration for approval and the work started within two weeks after approval. Figure 3.15 shows the transition from design phase to the construction phase.

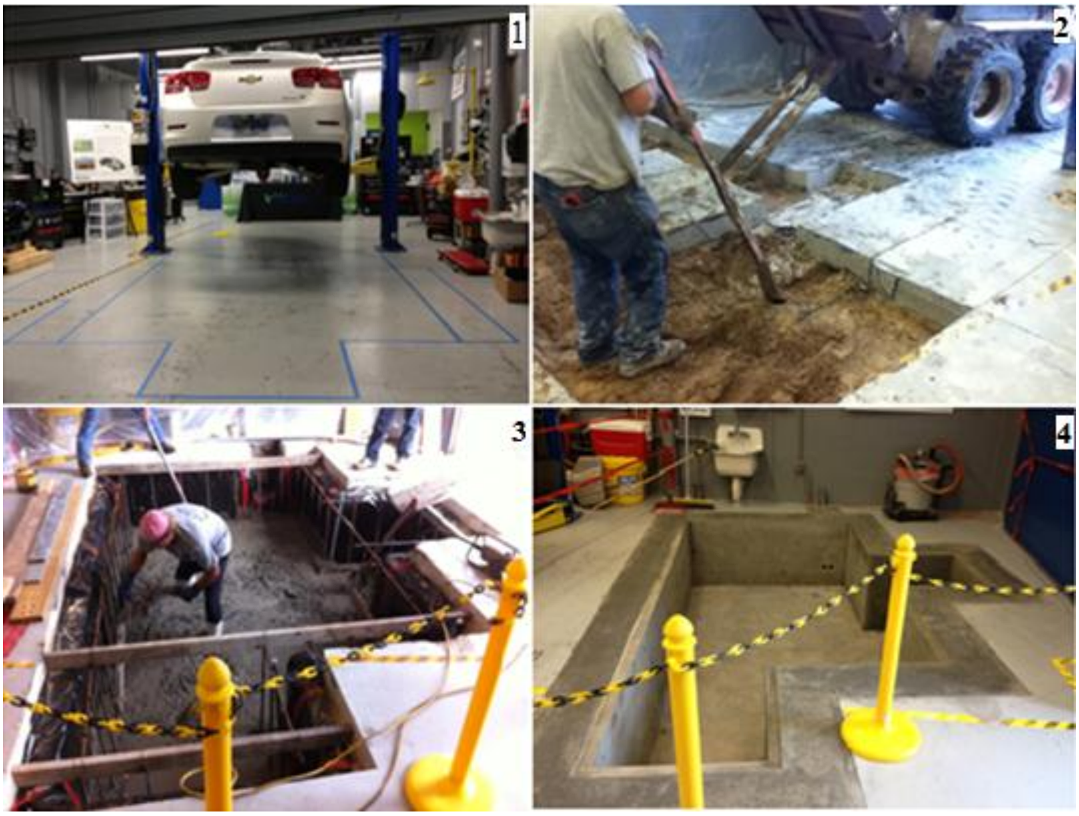


Figure: 3.15: Pit Construction

Fabrication of the Grate and Roller safety guards

Based on the design, the materials for the grates and the roller safety guard were ordered from Metals Depot, McMaster and ALRO metals and the fabrication was done in the machine shop. Fabrication involved cutting, assembling, surface finishing and painting. The cutting was done by using a cut off saw and the assembling was done by MIG welding. The grates and roller safety guards are assembled based on the dimensions of the constructed dyno pit to avoid issues related to installation. The figure below shows the fabrication of the roller safety guard.

Figure 3.16 Roller Safety Guard

Floor Anchors Installation

The concrete anchors are placed on the fore and aft side of the car based on the dimensions in figure 3.9. The D ring floor anchors are portable so they can be moved when there is no testing. Figure 3.17 shows the installed anchors on the floor.

Figure 3.17: Floor Anchor with D Ring

Chassis Dynamometer Installation

After the construction was finished, a fork lift and four slings at the ends of the roller were used to fit the dyno exactly inside the custom cast concrete pit. Four concrete anchors are used to anchor the chassis dyno to the pit floor. The figure below shows the installation of eddy current chassis dynamometer inside the pit.

Figure 3.18: Dyno Installation

It was difficult to place the dynamometer exactly inside the pit. The dyno was placed inside the pit based on the dimensions in Figure 3.18 to mark out the mounting hole location for the roller frame unto the floor of the test area. We anchored the frame to the test area floor using heavy-duty fasteners. The figure below shows the location of roller frame inside the pit.

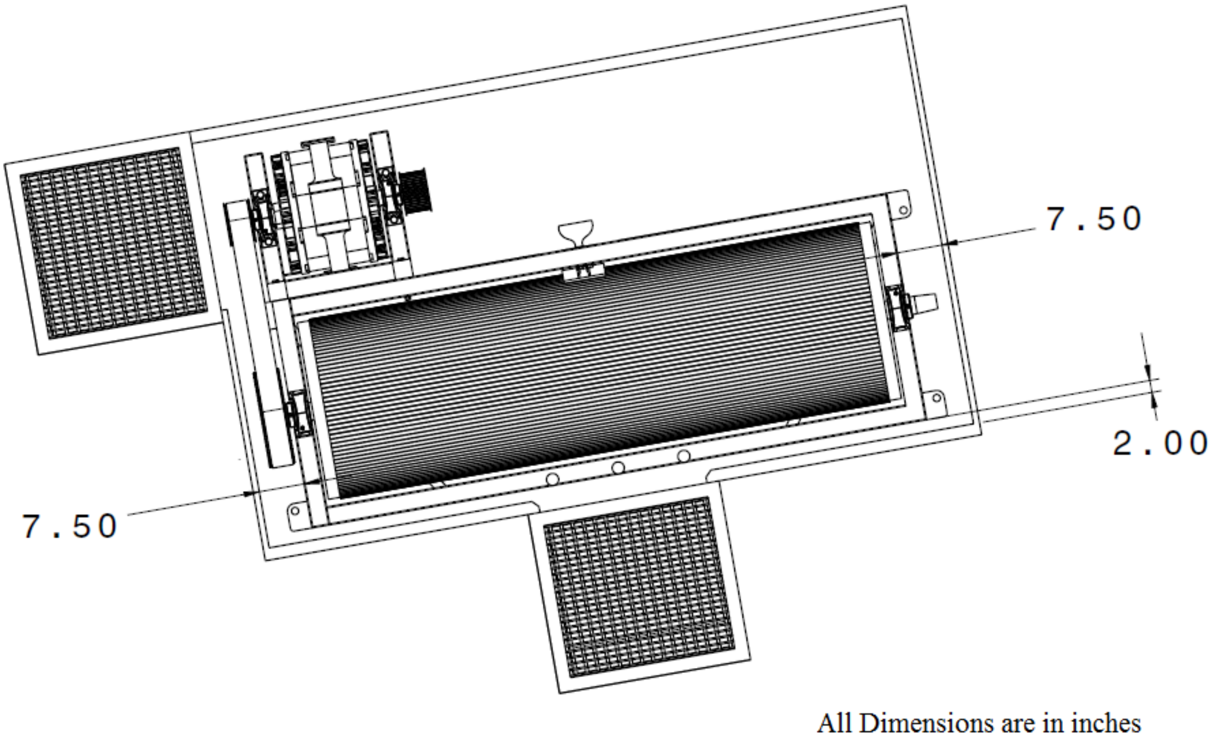


Figure 3.19: Dyno Installation Measurements

After the installation was completed, the deck plate was bolted to the top of the dyno assembly’s frame rail. The figure below shows the completed dyno installation.

Figure 3.20: Deck Plate Installation

Intake, Exhaust Fans and Grates Installation

The fan’s flange was modified to sit comfortably on top of the L clamp attached to the concrete. Minor variations, in the grate dimensions were necessary to allow it to fit properly inside the pit. This was because of the shrinkage in concrete structures. Figure 3.21 shows the installed intake fan and steel grate.

3.21: Intake Fan and Steel Grate

Air Brake

In order to install the air brake, an air line was placed between the dyno assembly’s air brake T fitting and the supplied palm button. The palm button is mounted on the wall and supplied from a machine shop air source regulated to approximately 90psi. The figure below shows the mounted air brake on the wall

3.22: Air Brake – Palm button

Eddy Current Setup

The current necessary to power the dynamite eddy current absorber is not proportional to the torque loading capability. Based on the land and sea specifications, the 96V eddy current absorber is hooked with a DYNOmite Power supply/control module. Figure below shows the mounted power supply/ control module.

3.23: Power Supply/ Control module

Engine Cooling System

Chassis dyno bay requires that we should provide enough airflow to keep the items like the engine, radiator, exhaust, underbody, etc. from getting too hot. It necessary to add a portable high power blower fans to the testing location aimed at those variable hot spots. Figure 3.24 shows the blower fan

Figure 3.24: Blower fan – McMaster-Carr Mfg. # 20445K15

This fan is usually positioned in front of the test vehicle radiator to generate sufficient airflow to simulate on road conditions for engine cooling purposes.

Exhaust System

The best way to protect EcoCAR students and garage employees from the potentially harmful gases released from vehicles running on the dyno is to capture it at the source. This means directly at the tailpipe.

The CFM rating and the engine's exhaust fumes temperature varies a lot based on the engine's performance. It is hard to match engine's CFM rating and exhaust fumes temperature with the fume/smoke exhauster's CFM and temperature handling limit. In order to avoid damage due to the exhaust fumes to the fan, a Y adapter is used to allow some fresh air inside the fan. Figure 3.25, 3.26, 3.27, 3.28 shows the fabrication of exhaust system.

Fig 3.25: Engine Exhaust Hose

Figure 3.26: Y Adapter

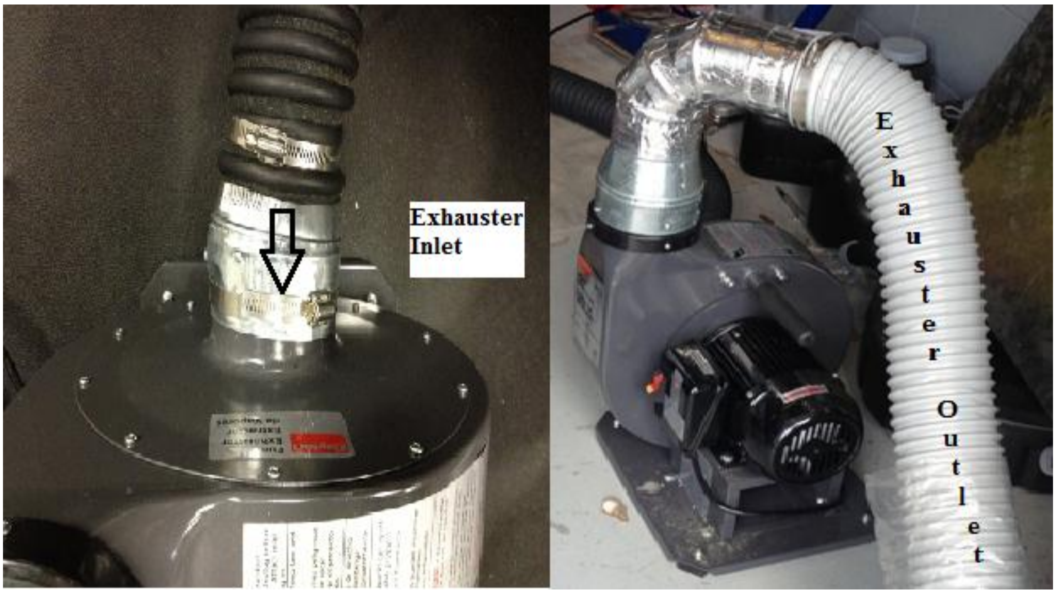


Figure 3.27: Fume/ Smoke Exhauster

As part of the modifications, the nine feet wire reinforced PVC inlet hose, which came with the exhauster, was replaced with the crushproof duct hose for exhaust fumes and a 90 degrees sheet metal exhaust elbow is used at the end of the outlet.

Figure: 3.28: Exhaust elbow

The dyno lab was setup based on the requirements defined in the chapter II. It involved the dyno acquisition, chassis dyno bay design, design and fabrication of safety frames, exhaust system fabrication, floor anchor location, Chassis dyno pit construction and dynamometer installation as per the requirements defined in chapter II. Therefore the installed eddy current chassis dynamometer in the dyno lab is ready to be commissioned.

Chapter IV

Chassis Dynamometer Commissioning

Commissioning is the process by which the installed eddy current chassis dynamometer is tested to verify if it functions according to its design objectives. It is necessary to test a vehicle in the chassis dynamometer under certain loading conditions. While testing, it is necessary to verify the systems such as Ventilation system, Exhaust system, Power output/control module, vehicle restraint straps, wiring and Data acquisition systems, to make sure everything is working in an efficient manner.

To commission the dynamometer, it was hard to find a FWD car on our campus. It is also impossible to test outside vehicles in our testing facility. We finally found a 2004 Ford Taurus, which was under auction, in our facility department. The specification of the car is below.

Type	Regular unleaded
Size	3.0L
Cylinders	6
Total Valves	12
Compression Ratio	10:1
Overall Length	197.7”
Overall Width	73”
Overall Height	57.8”
Wheelbase	108.5”
Transmission	4 - Speed Automatic
Curb weight	3306 lbs.

Table 4.1: 2004 Ford Taurus specifications

In order to start the dyno, a standard operating procedure was made to follow the steps involved in setting up the dyno and accessories necessary for testing.

Standard Operating Procedure (SOP)

A standard operating procedure (SOP) is a set of written instructions that document a routine to be followed while working with dynamometer in the EcoCar Lab. SOP is an integral part of a successful quality system as it provides individuals with the information to perform a job properly [23], and facilitates safety in the EcoCAR lab. The Standard Operating Procedure (SOP) is shown in table 4.2

Step	Action
1	Make sure there is enough space around the dynamometer for the free movement and safety purpose.
2	Make sure the safety frames are properly attached to the dynamometer frame on both ends of the roller
3	Place the D-rings plates on the floor, where the red head concrete anchors are located
4	Depress the air brake and then carefully drive a powered vehicle onto the rolls while watching out for clearance problems with any low hanging spoilers, etc.
5	Make sure the vehicle is centered based on the roller ends and the car lift pillars
6	Park the front wheels axle parallel to the roller and the wheels on the roller with a grade
7	Place appropriate size wheel chocks around the tires remaining on the ground (or lift) while you finish hooking up the restraining straps. Wheel chocks should never be relied upon (alone) for actual testing, as the vehicle will shift off of the rolls.
8	Setup the DYNOmite data acquisition computer and configuring DYNO-MAX before continuing to operate the dynamometer
9	Setup the exhaust blower fan with hose attached to the tailpipe and leave the other end outside the room
10	Setup the radiator cooling fan facing the vehicle
11	Switch on the inlet and exhaust fan, exhaust blower fan, radiator fan, room ventilation fan
12	Start the engine, release the parking brake, put the transmission into gear and

	gradually bring the drive wheels up to a low speed (i.e. 10 MPH) cruise. During this time, verify that the vehicle is tracking properly (repositioning as necessary) and also verify that the DYNOmite data acquisition system is receiving the roll's speed signal
13	Make sure the air brake is released before starting testing
14	Start the testing session, if everything is perfect
15	Inspect the condition of the straps and wheels on a frequent basis

Table 4.2: Safety Operating Procedure (SOP)

After the SOP was completed, the training date was set for 'April 13th' between the Land and Sea mentor and the EcoCAR students. The preliminary test for the commissioning of eddy current chassis dynamometer was conducted on April 9th. The test evaluated the vehicle restraint straps, ventilation system, and exhaust system without using the loads and data acquisition systems by driving the car on the roller at 80mph.

Dyno Test Setup

Vehicle setup was made based on the standard operating procedures and the equipment's involved in the testing are:

- Vehicle
- Eddy current chassis dynamometer
- Absorber power supply/Control module
- Dynamometer wiring harness
- Safety frames
- Vehicle floor anchors and tie down straps
- Inlet and exhaust fan
- Radiator fan
- Exhaust blower fan with hose

- Data acquisition computer
- Data computer, RS 232 cable, USB cable

Figure 4.1 shows the vehicle setup for testing:

Figure 4.1: Vehicle setup for testing

Data Acquisition Harness

The 28 channel full function DYNOmite data acquisition harness supports many optional transducers and controller functions beyond the standard harness leads. After referring to the labels in the harness and the accessories available for our application, the connections were identified.

Ground is the DYNOmite harness’s black main system ground lead as well as the ground for many accessories. It must be always clamped directly to the single main engine/battery/building/chassis/power-supply ground.

Torque (Strain1) input lead carries the signal from the DYNOmite's absorber mounted strain gage equipped torque arm or millivolt load cell. Plug the matting 4 pin connectors from both the DYNOmite harness and the torque source together. This lead was extended for the remote mounting of the console.

Servo Control lead drives the electronic auto load servo. It has a six pin DIN connector which should be plugged into the mating female receptacle in the eddy current control module.

Absorber RPM – C (Frequency 2) input lead supports the DYNOmite inductive and toothed gear RPM pickup knits. The sensor's long lead routes back to the DYNOmite harness's matching 5 – pin DIN jack shaft connector. For obtaining MPH from the chassis dynamometer with the eddy current absorber or monitoring the shift ratio via a secondary jack shaft's RPM, the pickup can read a rotating magnet in a shaft mounted.

Clamp-on Inductive RPM Pickup is a kit which includes a non-directional inductive pickup clamp for the high tension spark plug, primary coil or a fuel injector's lead. The conditional output from the clamp's harness delivers a clean square wave RPM signal ready to plug directly into the DYNOmite pro data acquisition computer's tachometer channel (yellow wire @ 3.5 trigger voltage).

DYNOmite Data Computer and Controller

The DYNOmite data acquisition computer board support either RS232 serial (DB 9 pin port) or full speed USB communications with a DYNO-MAX equipped PC. In order to communicate with the DYNOMAX, both the PC and the DYNOmite board set must be set to same communication mode [9].

Figure 4.2 shows DYNOmite Pro data acquisition computer

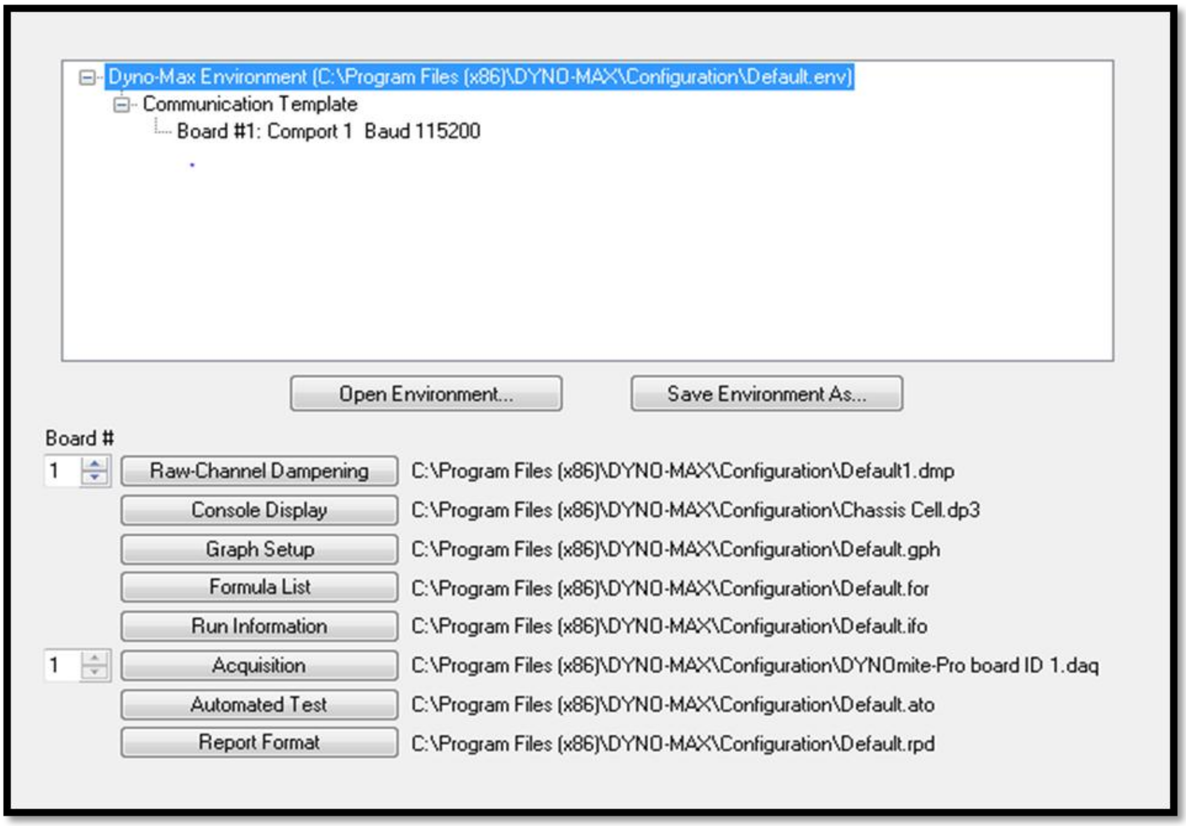
Figure 4.2: DYNOmite Pro Data Acquisition Computer

Initially it was easier to use USB, which is more reliable than RS232 cable to connect the data acquisition computer with the DYNOMAX software laptop. Because of the Electro interference, I decided to use RS232 (DB 9 pin) as suggested in the DYNOmite Owner's Manual – section 6.7 and 6.8 for more information regarding the serial and USB Hook-Up.

DYNOMAX Software

DYNOMAX software allows a personal computer to monitor and control the dynamometer. It communicates with via RS-232 or USB with DYNOmite computer data acquisition board. The DYNOmite computer handles most of the high speed data acquisition system and controls the dynamometer to reduce the load on the PC. It primarily handles the data display, storage, post processing and printing.

DYNOMAX takes advantage of the PC's flexibility, permitting expanding and adapting the dynamometer system as needs change. Due to the extensive customization possible, initially configuring the environment is more important part of getting started as shown by Figure 4.3.



Dyno-Max Environment (C:\Program Files (x86)\DYNO-MAX\Configuration\Default.env)
Communication Template
Board #1: Comport 1 Baud 115200

1 Raw-Channel Dampening C:\Program Files (x86)\DYNO-MAX\Configuration\Default1.dmp
Console Display C:\Program Files (x86)\DYNO-MAX\Configuration\Chassis Cell.dp3
Graph Setup C:\Program Files (x86)\DYNO-MAX\Configuration\Default.gph
Formula List C:\Program Files (x86)\DYNO-MAX\Configuration\Default.for
Run Information C:\Program Files (x86)\DYNO-MAX\Configuration\Default.ifo
1 Acquisition C:\Program Files (x86)\DYNO-MAX\Configuration\DYNOmite-Pro board ID 1.daq
Automated Test C:\Program Files (x86)\DYNO-MAX\Configuration\Default.ato
Report Format C:\Program Files (x86)\DYNO-MAX\Configuration\Default.rpd

Figure 4.3: Dynomax Environment Files

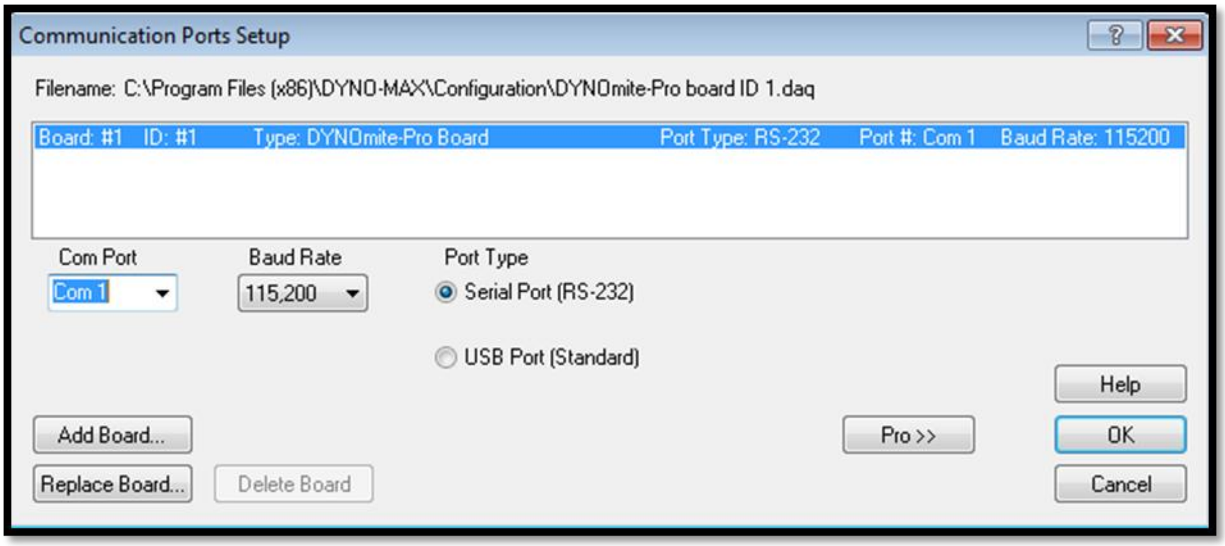
DYNO-MAX’s console set up, graph set up, DYNOmite channel calibration, etc., are all stored in individual configuration files. After using DYNO-MAX for a few weeks a new configuration library was created. After creating a new configuration files specific to our test needs, it is far less tedious setting up for a new test session. It is easier to pull together an appropriate set of configuration files with its environment (.env) files because each environment file can point to a different group of your custom configuration files. Steps involved in creating a new configuration are:

Step	Action
1	Go to Windows Start button and select Programs – DYNO-MAX.
2	Create a DYNO-MAX environment file contains the list of eight configuration files that control settings.

3	Power up the DYNOmite data acquisition computer.
4	Select Electronics – communication ports set-up and verify that “board: #1 id: #1 type: DYNOmite-basic board
5	It is necessary to choose the communication mode in DYNOMAX software from DYNO-MAX’s “electronics – communication ports set up” menu.

Table 4.3: DYNOMAX Software Setup - I

In our case, it is verified that the communication is in "Serial Port (RS-232)" mode. The dialog box below shows the options of Electronics - Communication Ports Set Up.



Communication Ports Setup

Filename: C:\Program Files (x86)\DYNO-MAX\Configuration\DYNOmite-Pro board ID 1.daq

Board: #1 ID: #1 Type: DYNOmite-Pro Board Port Type: RS-232 Port #: Com 1 Baud Rate: 115200

Com Port: Com 1

Baud Rate: 115,200

Port Type:

● Serial Port (RS-232)

○ USB Port (Standard)

Figure 4.4: DYNO-MAX - Communication Port Setup

Console Setup

The Console uses VCR like buttons to control, recording and playback. The entire console gauges, titles, ranges, scaling, resolution, units, chart axis, alarm limits and actions was reconfigured to suit our own testing.

Step	**Action**
6	Customize the console based on the test and accessories available using Tools-Options-Console Design Editor

Table 4.4: DYNOMAX Software Setup - II

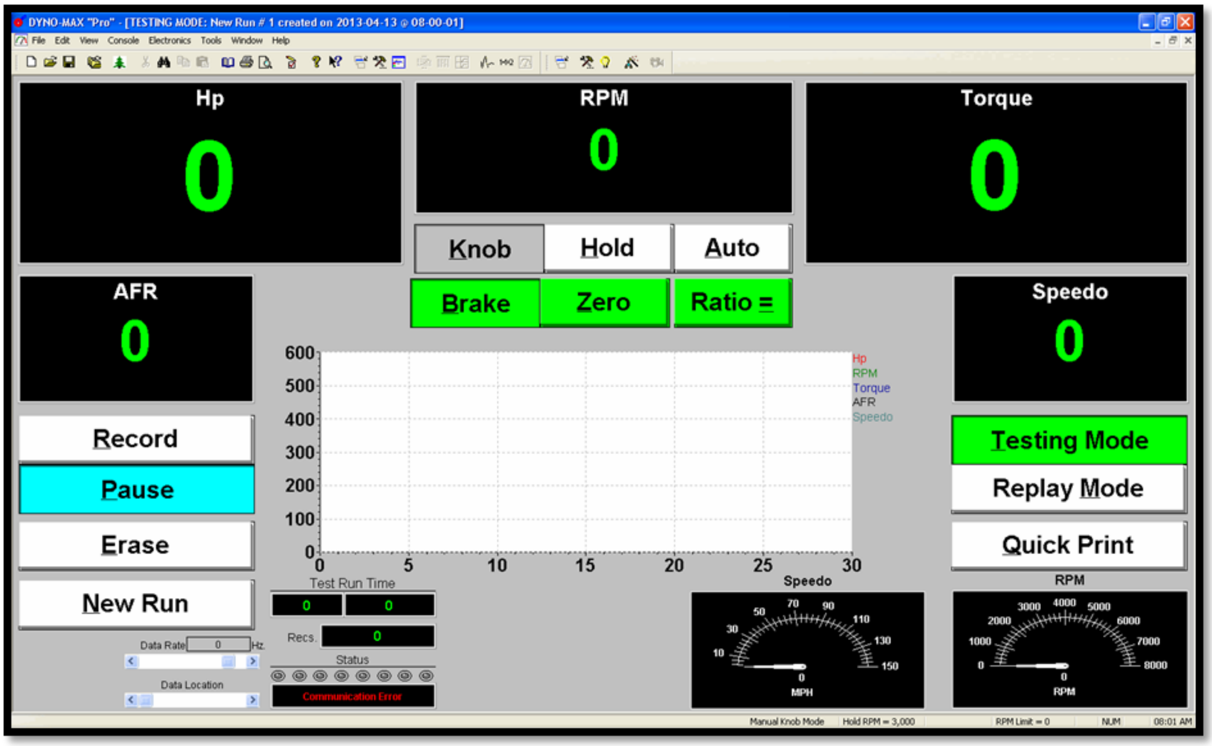


Figure 4.5: ERAU DYNOMAX Console

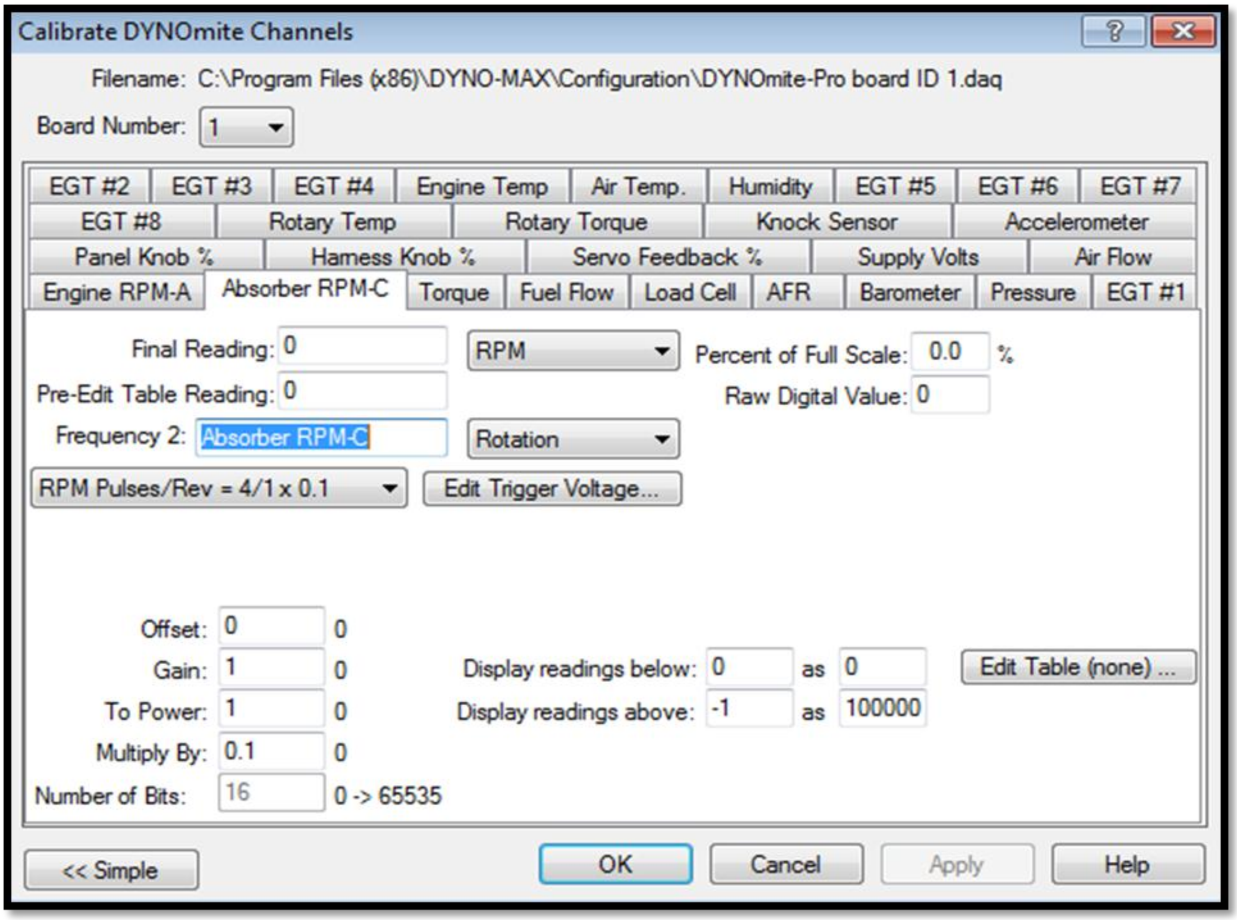
Calibration of Channels

Calibration of Channels is the place where we can assign names to each DYNOmite data acquisition computer hardware channel, calibrate sensors and edit custom calibration tables. Here we can modify the setup parameters for all the individual channels. It is necessary to make changes in this window, whenever we change transducers, RPM Sources etc.

Step	Action
7	Calibrate DYNOmite channels using the menu, Electronics - Calibrate DYNOmite channels

Table 4.5: DYNOMAX Software Setup - III

Figure 4.6 below shows the calibration of the channel absorber RPM-C


Calibrate DYNOmite Channels

Filename: C:\Program Files (x86)\DYNO-MAX\Configuration\DYNOmite-Pro board ID 1.daq

Board Number: 1

Final Reading: 0 RPM

Percent of Full Scale: 0.0 %

Pre-Edit Table Reading: 0

Raw Digital Value: 0

Frequency 2: Absorber RPM-C Rotation

RPM Pulses/Rev = 4/1 x 0.1

Offset: 0 0

Gain: 1 0

To Power: 1 0

Multiply By: 0.1 0

Number of Bits: 16 0 -> 65535

Display readings below: 0 as 0

Display readings above: -1 as 100000

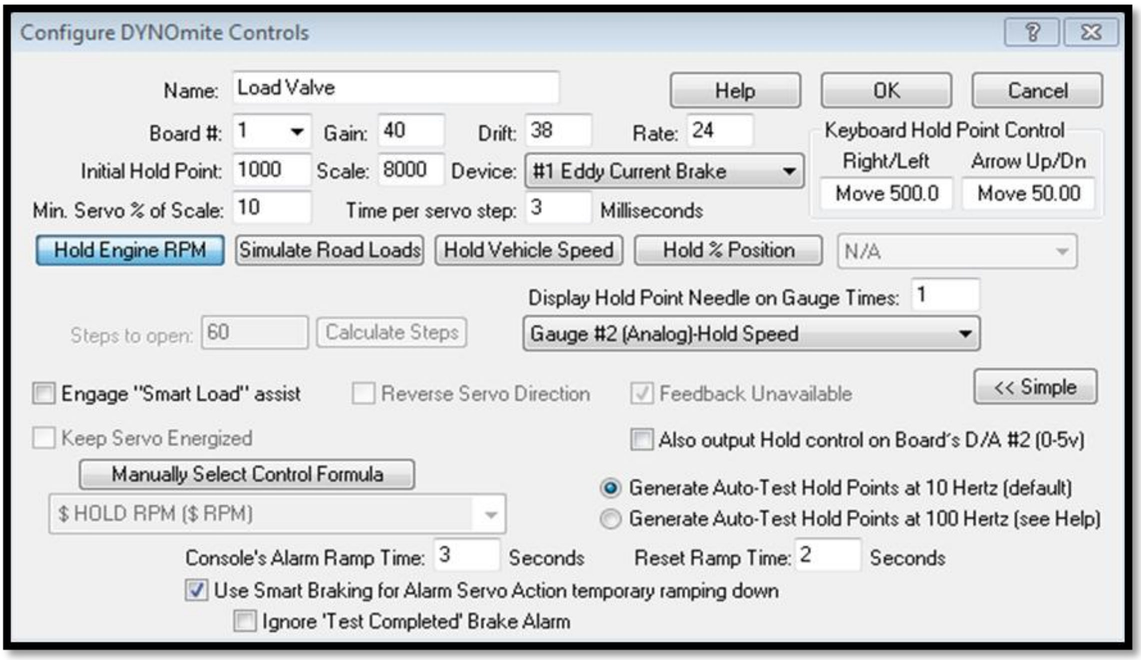
Figure 4.6: Calibrate DYNOmite Channels

Configure DYNOmite Controls

In configuring DYNOmite controls, tuning PID (proportional, integral, derivative) controls seems like more of an art than a science. It is easier if we have good understanding of what each component calculates its actions from. Below, each of the DYNOmite's PID factor multipliers (gain, drift, and rate) is explained individually. This example is written in terms of an engine RPM based load control valve.

Step	Action
8	Configure DYNOmite controls using the menu, Electronics - Calibrate DYNOmite Controls

Table 4.6: DYNOMAX Software Setup - IV



Name: Load Valve

Board #: 1 Gain: 40 Drift: 38 Rate: 24

Initial Hold Point: 1000 Scale: 8000 Device: #1 Eddy Current Brake

Min. Servo % of Scale: 10 Time per servo step: 3 Milliseconds

Keyboard Hold Point Control
Right/Left: Move 500.0
Arrow Up/Dn: Move 50.00

N/A

Display Hold Point Needle on Gauge Times: 1

Steps to open: 60

Gauge #2 (Analog)-Hold Speed

☐ Engage "Smart Load" assist
☐ Reverse Servo Direction
☑ Feedback Unavailable
☐ Keep Servo Energized
☐ Also output Hold control on Board's D/A #2 (0-5v)

$ HOLD RPM ($ RPM)

● Generate Auto-Test Hold Points at 10 Hertz (default)
○ Generate Auto-Test Hold Points at 100 Hertz (see Help)

Console's Alarm Ramp Time: 3 Seconds Reset Ramp Time: 2 Seconds

☑ Use Smart Braking for Alarm Servo Action temporary ramping down
☐ Ignore 'Test Completed' Brake Alarm

Figure 4.7: Configure DYNOmite Controls

This Gain (proportional multiplier) adjusts how much the controller instantaneously moves in response to a change in vehicle speed on a chassis dynamometer. For example, with twice as large a gain multiplier, the load control's action doubles in response to any RPM increase.

This Drift (integral multiplier) adjusts the load valve's aggressiveness in removing longer term steady state errors between actual Engine RPM and the desired Hold RPM. The larger the drift multiplier the more quickly the controller works (gradually) to eliminate holding RPM deviation.

The larger the Rate (derivative multiplier) the more the controller "fights" changes in actual engine RPM vs. the desired Hold RPM. The rate multiplier scales the DYNOmite algorithm that compensates for control latency in order to decide how far momentarily "over travel" the load controls to steady a rapidly accelerating engine.

In configure DYNOmite controls, if the ‘Hold Engine RPM’ push button is active, the DYNOmite’s optional electronic load control servo will adjust the dynamometer’s absorber to hold specific hold RPM. It is not necessary to engage the option ‘engage smart load assist’ for our system [10].

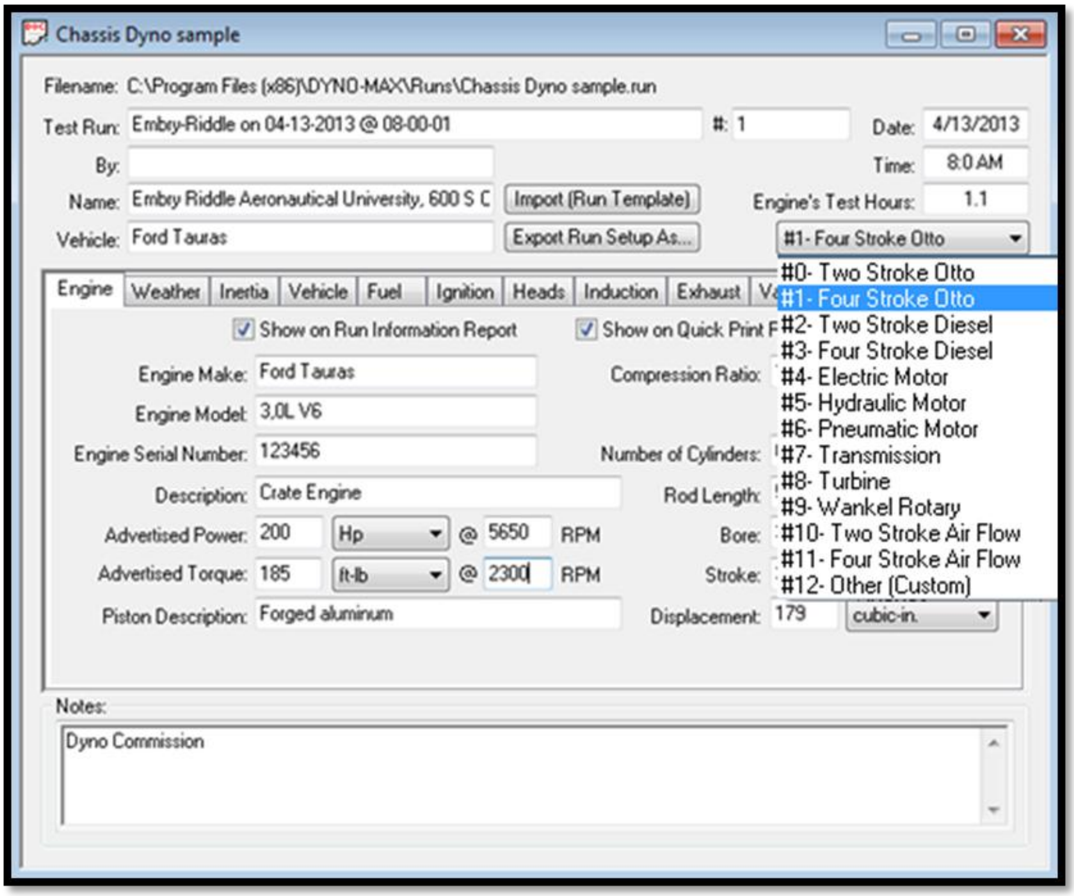
Run Information

The DYNOMAX feature displays all the details related to the vehicles and dynamometer. All information under run information tab must be entered because some information is required by the DYNOMAX system formulas.

Step	**Action**
9	Click File - Open Run/ New Run to load the test Run Information file.
10	It is necessary to start with the test device type in the run information because it selects an appropriate set of tab screens in the run information window
11	It is necessary to fill all the appropriate information regarding engine, weather, inertia etc.
12	It is necessary to select the RPM Source and Torque Under the Run Information Dyno tab
13	Make sure the absorber’s inertia and parasitic drag values have been entered, etc.

Table 4.7: DYNOMAX Software Setup – V

As part of commissioning, the run information was filled based on the data specifications of Ford Taurus and the corresponding test date in order to get accurate results. The RPM source, gear and drive ratio’s must all set correctly to return accurate RPM, torque and power data. Figure 4.8 shows the run information details and the types of test devices.

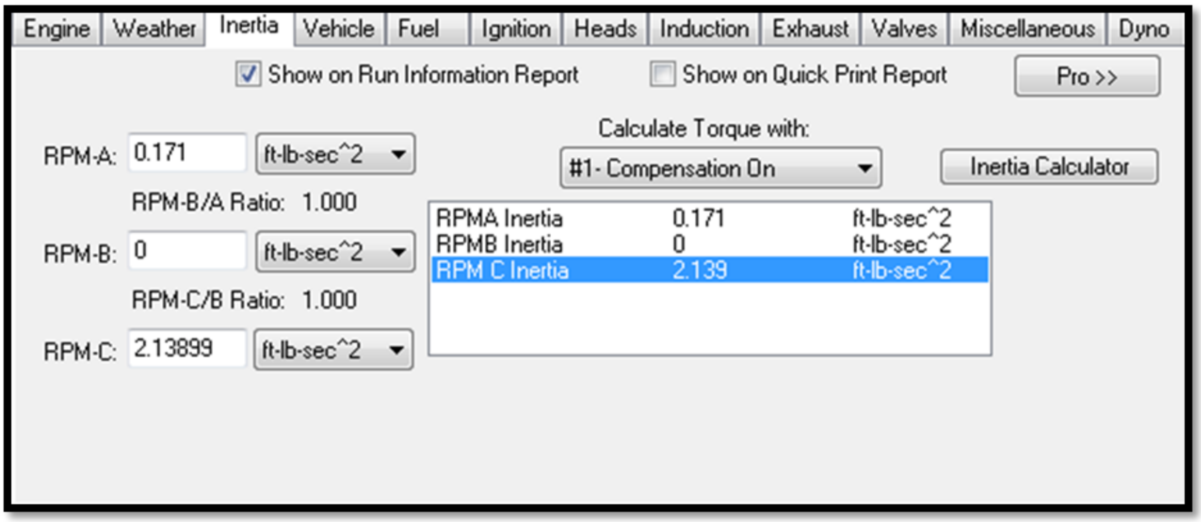


Filename: C:\Program Files (x86)\DYNO-MAX\Runs\Chassis Dyno sample.run
Test Run: Embry-Riddle on 04-13-2013 @ 08-00-01
#: 1
Date: 4/13/2013
By:
Time: 8:0 AM
Name: Embry Riddle Aeronautical University, 600 S C
Engine's Test Hours: 1.1
Vehicle: Ford Tauras
#1- Four Stroke Otto
☑ Show on Run Information Report
☑ Show on Quick Print F
Engine Make: Ford Tauras
Engine Model: 3.0L V6
Engine Serial Number: 123456
Description: Crate Engine
Advertised Power: 200 Hp @ 5650 RPM
Advertised Torque: 185 ft-lb @ 2300 RPM
Piston Description: Forged aluminum
Compression Ratio:
Number of Cylinders:
Rod Length:
Bore:
Stroke:
Displacement: 179 cubic-in.
Notes:
Dyno Commission

Figure 4.8: Run information file

In our case, the RPM – C is selected as absorber inertia to use the smart ratio feature. It is much easier to test a vehicle using RPM – C rather than an engine-RPM pickup.

It is necessary to enter the appropriate weight and coast down G’s for the vehicle being tested. The curb weight of the compact vehicle is nearly around 3500lb and its equivalent coast down G value is .031.



☑ Show on Run Information Report

☐ Show on Quick Print Report

Calculate Torque with: #1 - Compensation On

RPM-A: 0.171 ft-lb-sec^2

RPM-B/A Ratio: 1.000

RPM-B: 0 ft-lb-sec^2

RPM-C/B Ratio: 1.000

RPM-C: 2.13899 ft-lb-sec^2

RPMA Inertia	0.171	ft-lb-sec^2
RPMB Inertia	0	ft-lb-sec^2
RPM C Inertia	2.139	ft-lb-sec^2

Figure 4.9: Run Information – Inertia

Run Information - Smart Ratio

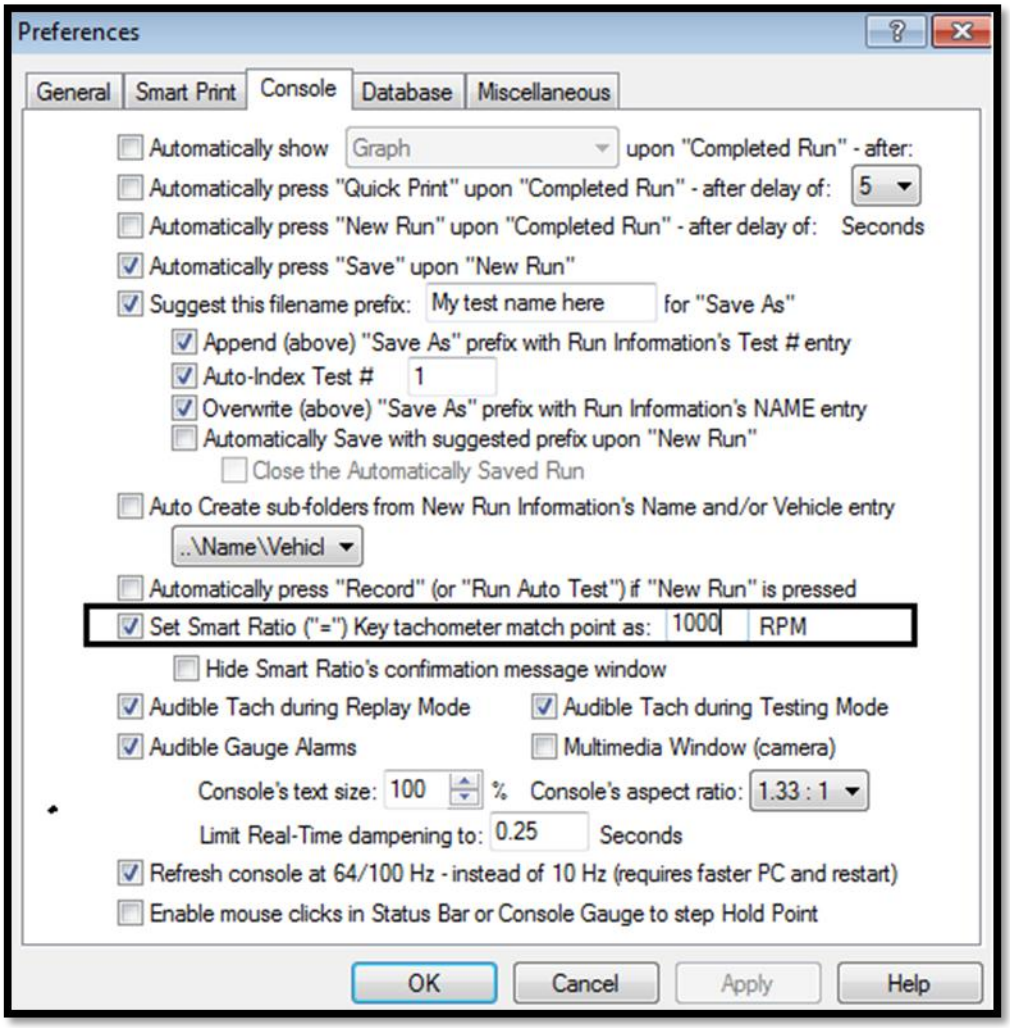
Smart Ratio is used during chassis dyno testing to semi automatically calculate and set the run information tab's gear ratio field so that DYNOMAX's tachometer[14] and the vehicles own tachometer's match. This avoids having to manually calculate the final effective gear ratio through all of the transmission, rear axle, and tire to roller diameter ratios manually.

It makes it easy to display Engine RPM by automatically entering the correct "Gear Ratio" when we don't have a yellow tachometer lead signal. In our case, we are only capturing the dynamometer's roller speed via Shaft Magnet. The steps involved in smart ratio are

i. Set the 'Smart Ratio value under Tools – Preferences – console and give a value as 1000 RPM. The figure below shows the smart ratio setup.

ii. During console operation, hold the engine at the exact “match point RPM” on the vehicle’s tachometer and then press the console’s “=” key.

iii. Smart ratio brings up a confirmation window to update the run information – vehicle tab’s Gear Ratio, so that the DYNOMAX’s tachometer matches the vehicles. The Smart Ratio setup below [10].



- ☐ Automatically show Graph upon "Completed Run" - after:
- ☐ Automatically press "Quick Print" upon "Completed Run" - after delay of: 5
- ☐ Automatically press "New Run" upon "Completed Run" - after delay of: Seconds
- ☑ Automatically press "Save" upon "New Run"
- ☑ Suggest this filename prefix: My test name here for "Save As"
  - ☑ Append (above) "Save As" prefix with Run Information's Test # entry
  - ☑ Auto-Index Test # 1
  - ☑ Overwrite (above) "Save As" prefix with Run Information's NAME entry
  - ☐ Automatically Save with suggested prefix upon "New Run"
    - ☐ Close the Automatically Saved Run
- ☐ Auto Create sub-folders from New Run Information's Name and/or Vehicle entry
  - ..\Name\Vehicl
- ☐ Automatically press "Record" (or "Run Auto Test") if "New Run" is pressed
- ☑ Set Smart Ratio ("=") Key tachometer match point as: 1000 RPM
  - ☐ Hide Smart Ratio's confirmation message window
- ☑ Audible Tach during Replay Mode
- ☑ Audible Tach during Testing Mode
- ☑ Audible Gauge Alarms
- ☐ Multimedia Window (camera)
- Console's text size: 100 %
- Console's aspect ratio: 1.33 : 1
- Limit Real-Time dampening to: 0.25 Seconds
- ☑ Refresh console at 64/100 Hz - instead of 10 Hz (requires faster PC and restart)
- ☐ Enable mouse clicks in Status Bar or Console Gauge to step Hold Point

Figure 4.10: Smart Ratio Setup

It is necessary to include the drive ratio in the run information dyno tab. For our 30" eddy current chassis dynamometer, the drive ratio is 2.368.

Chassis Dynamometer Testing

As the vehicle accelerates the roll, the DYNOmite computer and DYNO-MAX software monitors the roll and engine RPM, run time, rate of acceleration and also the absorber torque. It uses this information to calculate and display the applied power. In eddy current chassis dynamometer, the load control module (under manual or computer regulation) can easily adjust the resistance the rolls apply to the vehicle's tires. By increasing or decreasing the absorber load, it is possible to simulate various road conditions at the throttle opening of our choice. Such control is ideal for troubleshooting problems, tuning fuel injection systems, etc.

When using the Electronic Servo Load Control option, it is possible to specify a specific holding speed or engine RPM. The computer will automatically maintain under most throttle settings. Various Auto Tests may also be run using the servo control to sweep or step the engine over predefined test points.

DYNO-MAX has a special 'Road Load Simulation' mode. It controls the vehicle speed based on the cumulative power applied during the test calculated against the user input vehicle drag and weight information. In this mode, we noticed an exponentially increasing load being applied to the vehicle, the faster and quicker it is accelerated. Conversely, there will be a coasting effect during deceleration. If the entered drag settings are appropriate, this becomes a very convenient mode to do engine management system mapping and diagnostic testing. The steps involved in testing procedure are:

Step	Action
1	Power up the DYNOmite's computer and go to an appropriate Real-Time data display screen.
2	Be sure to review all the required fields in the Run Information panel, as these settings influence test results
3	Prepare the Console for Real Time data collection by clicking on its Testing Mode

	button. If the DYNOmite data acquisition computer is actively communicating with DYNO-MAX, the status message will display ‘Ready’.
4	Start the engine and compare the DYNOmite’s RPM display with the engine's tachometer. Minor variation between the tachometers is normal
5	Apply about quarter throttle and practice opening and closing the load valve manually to control raising and lowering the engine’s RPM.
6	Add a bit more throttle and continue practicing the art of moving the engine RPM up and down with just the load valve (leaving the throttle fixed).
7	Continue making practice dyno runs (using more throttle each time) until, at full throttle, we will able to make a controlled sweep of the engine’s power band using just the load valve.
8	Once we are comfortable running the engine at full throttle (under manual load valve control), we will be able to glance at the data screen to monitor torque, Hp, etc. during testing.
9	To find peak horsepower, just adjust the load valve to the RPM that yields the highest (steady state) horsepower reading.
10	To start recording an automated test, press the ‘TEST’ button From the standard Real Time data display screen with the engine idling and warmed up
11	If you run manually, enter appropriate settings for controlling data capture thresholds and playback rates using edit – edit Console Setup – Smart Record.
12	When we finished collecting data, smoothly cut the throttle while simultaneously un-loading the idling engine by closing the load valve.
13	Our test data is now ready to playback for analyzing.

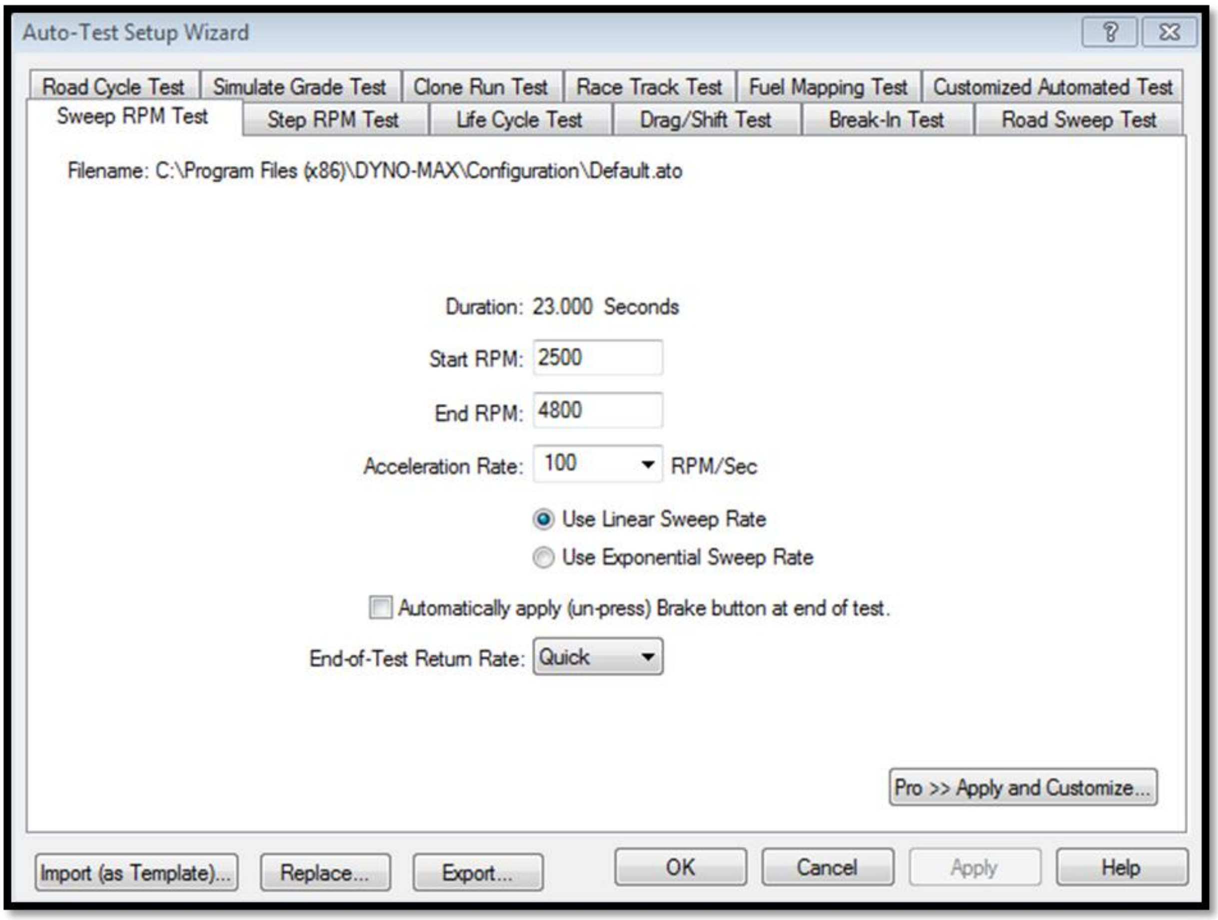
Table 4.8: Testing Procedure

Automated Test Setup

Automated tests are files containing lines of instructions for DYNO-MAX to consecutively pass to the DYNOmite’s servo control system. These auto test runs are primarily meant to trigger the recording buttons when running the dynamometer.

We wanted to run the standard sweep or step testing under servo load control to verify how the auto load control system provides the chosen RPM. To do this, it was necessary to switch the servo control mode with either the ‘Hold Engine RPM’ or ‘Hold Vehicle Speed’ button.

Based on the chassis dynamometer testing procedures, we started the engine and compared the DYNOmite’s RPM display with the engine's tachometer until it became equal. We made couple of practice dyno runs until full throttle is achieved. Figures 4.11 show an example of automated sweep RPM test setup.



Filename: C:\Program Files (x86)\DYNO-MAX\Configuration\Default.ato

Duration: 23.000 Seconds

Start RPM: 2500

End RPM: 4800

Acceleration Rate: 100 RPM/Sec

● Use Linear Sweep Rate

○ Use Exponential Sweep Rate

☐ Automatically apply (un-press) Brake button at end of test.

End-of-Test Return Rate: Quick

Figure 4.11: Auto Test Setup Wizard

The duration time in the setup displays the approximate elapsed time that the current sweep configuration will take to execute. The ‘Start RPM’ and ‘End RPM’ specify the initial and final RPM limits. The linear sweep rate will accelerate the engine at a constant rate whereas exponential sweep rate accelerates the engine over an exponential decreasing rate

[10]. For our test, this wizard designs a recording pass over 2500 RPM and at the selected linear acceleration rate.

Data Analysis

During playback, the DYNOmite data computer can increase data usability by filtering and averaging many individual reading sets before displaying them as a single "clean" data point set. The playback was set to automatically ignore any data sets captured while the engine was sweeping too rapidly.

Step	Action
1	To open a saved run and to examine its test data, Select View - Graph to display the Run's (current default format) graph.
2	The graph's window has special Toolbar Icons for zooming, panning, clipping segments, examining data points, print previewing, and graph set up.
3	Click on the "Hp vs. RPM Steps" tab, and then click on "OK." Notice that the graph draws with Engine RPM as its X-axis.

Table 4.9: Data Analysis Procedure

After test data has been collected, simply press the print button to display the last run data.

Result Summary

In order to commission an eddy current chassis dynamometer, it is necessary to verify the dynamometer operation. The preliminary test for the commissioning of eddy current chassis dynamometer was conducted on April 9th, 2013. The test was conducted in two parts. The first test evaluated the operation of eddy current chassis dynamometer along with safety vehicle restraint straps, ventilation system, and exhaust system without using the loads and data acquisition systems by driving the car on the roller at 80mph.

The second test ran a couple of sweep RPM tests and an engine performance test. The Sweep RPM test is the test which allows the engine to accelerate from its starting RPM to ending RPM under auto load control or manual load control targets a specific rate of acceleration. The loads applied can be varied while the test is running either by using the knob in the control module or by using the computer keyboard.

The table below shows the Sweep RPM Test result of the engine.

RPM (RPM)	Horse Power (Hp)	Torque (ft-lb)
2500	68.06931	143
2600	70.29703	142
2700	71.97258	140
2800	74.1051	139
2900	75.64737	137
3000	77.68469	136
3100	79.68393	135
3200	82.25438	135
3300	85.45316	136
3400	87.39528	135
3500	88.6329	133
3600	92.53618	135
3700	97.22011	138
3800	99.84768	138

3900	101.7327	137
4000	102.818	135
4100	105.3884	135
4200	107.1592	134
4300	108.8919	133
4400	108.9108911	130
4500	110.5293222	129
4600	111.2338157	127
4700	111.8621478	125
4800	114.2421935	125

Table 5.1: Sweep RPM Test Result

From the result, it is shown that the current into the eddy current absorber is varied under the auto load control to provide the chosen RPM from 2500 RPM to 4800 RPM at a sweep rate of 100 RPM.

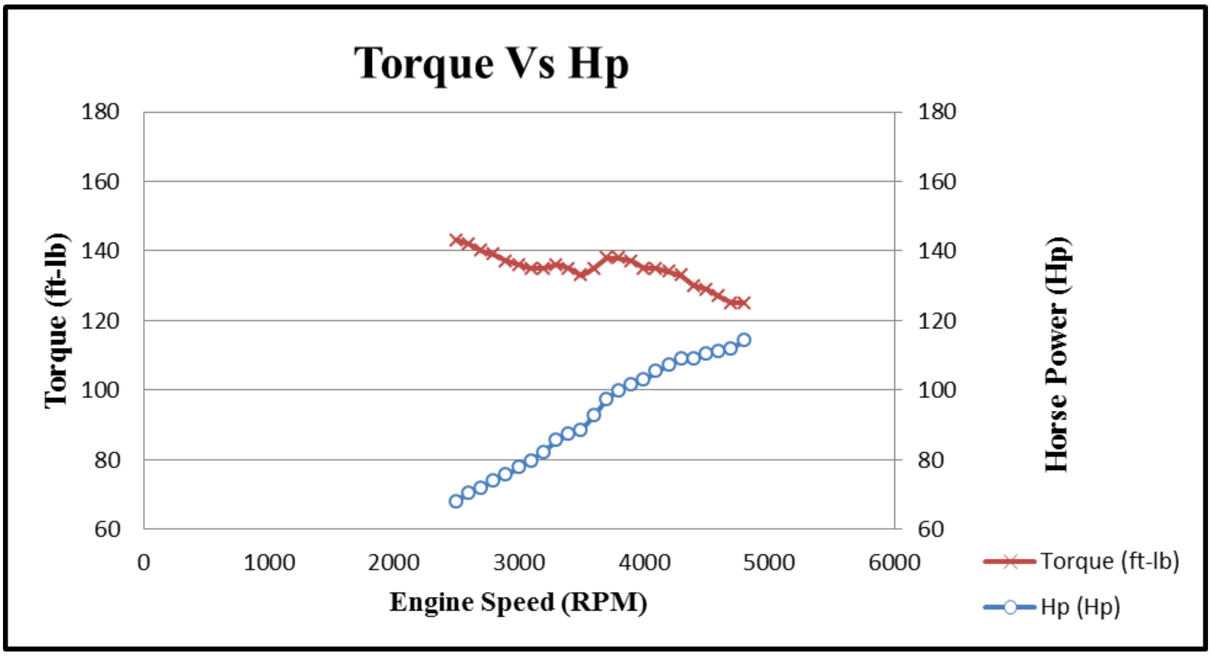


Figure 5.1: Experimental Sweep RPM Test Result

From the above figure 5.1, it was noticed that the test results depend on certain factors. This includes air temperature, oil temperature, atmospheric conditions, and most importantly, the length of time at which the engine remains at a given load level. The test results also include the rate of sweep.

The torque and horsepower stored in the DYNOMAX are the true readings Observed under the atmospheric conditions that existed during the test. However, if we need to compare testing from one day to another or compare test data taken at a different altitude, we need to correct the standard atmospheric conditions.

The test was also conducted to measure the peak torque and peak horse power by using the inertia method. The graph below shows the Performance curve of a Ford Taurus.

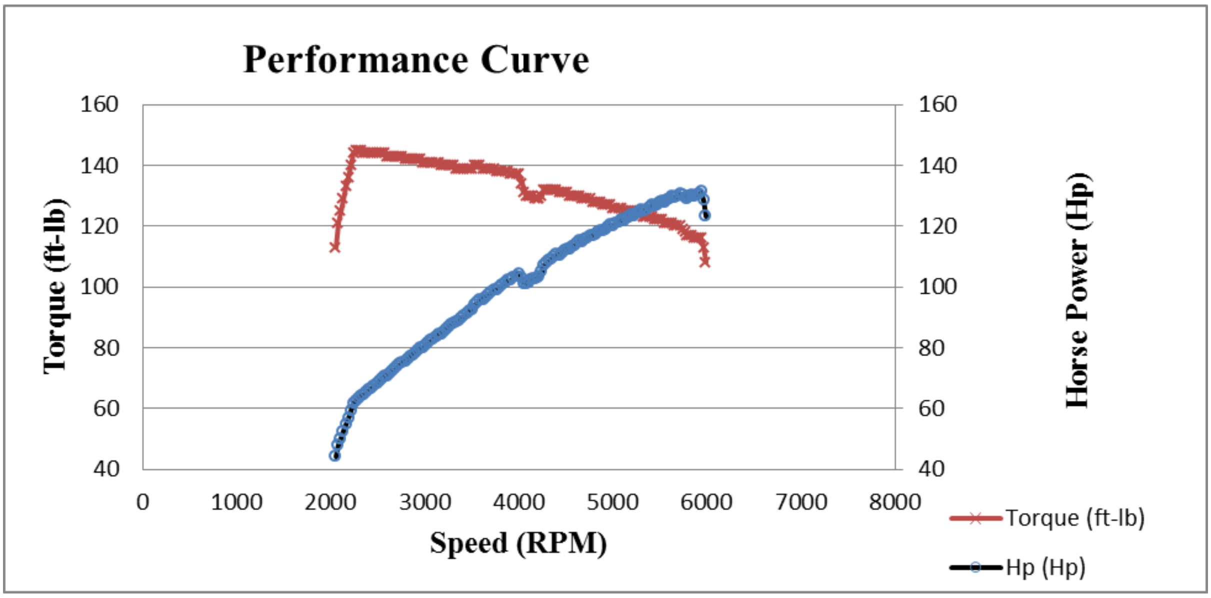


Figure 5.2: Experimental Performance Curve

Peak Horse Power (Hp)	131.35 @ 5947 RPM
Peak Torque (ft-lb)	145 @ 2300 RPM

Figure 5.3: Experimental Performance Table

The engine torque and horsepower values vary with engine speed. In the typical performance curve (figure 5.2) above, notice that maximum torque is developed at low to moderate RPM while brake horsepower (the power available at the end of the crankshaft) continues to rise into the high RPM range. At higher RPM the torque and horsepower curves begin to drop due to difficulties in the engine's breathing at the higher speeds.

During commissioning, we ran several tests continuously for one hour a day for three days. We drove the Ford Taurus up to 80 MPH and achieved maximum engine speed of about 5953 RPM using Auto load control. The eddy current chassis dynamometer had no issues in running continuously for an hour at a time. This shows that the EcoCAR Lab has an efficient air cooled eddy current chassis dynamometer.

It was verified that the floor anchors and restraint straps were able to hold a 70MPH vehicle while running auto load control tests. By looking at the data recorded during test, it is appropriate to tell that the wiring systems and data acquisitions systems are working in an efficient manner without any issues.

Based on the results, it was found that the engine's peak horsepower is 15% lower than the rating provided by the manufacturer. Some legitimate reasons could be that we used a nine year old engine and an inexperienced testing mechanic.

The EcoCAR Lab Temperature:

As part of commissioning, the room temperature was measured before and after the dyno testing in about one hour difference. The room temperature increased to 3.2 degree Fahrenheit after one hour testing.

Day	Temperature (F) - 8 A.M	Temperature (F) – 9 A.M
04/13/2013	76.4	79.6

Table 5.2: EcoCAR Lab temperature

Based on the weather report, it is verified that the outside environment temperature contributed 73.6 % (2.36 F) more heat than the heat air released from the dyno pit.

The ventilation fans inside the pit, the radiator fan, and the ventillation fan combinely added advantage to the proper ventillation . There was no trace of engine exhaust gas to circulate inside the room because it was evacuated directly out of the room by using the blower and hose setup.

Chapter V

Discussions, Conclusions and Future Recommendations

Discussions

While testing, it was found that proper operation is vital to get usable data from any dyno session. Due to the inertial energy, only reasonably steady state dyno readings are meaningful. Always keep acceleration below 800 RPM per second. Readings taken while rapidly decelerating the engine with the load valve include actual engine power plus the flywheel energy from the decelerating crank train. This provides an inflated wrong Hp reading. This is not a defect. It is, at that moment, the actual power being delivered at the output shaft. It is not power that the engine can sustain alone. Conversely, if the engine is rapidly accelerating, we got a low reading. So, maintain reasonably steady RPM with the load valve while reading power.

It was also found that there is a slight delay between moving the load valve and actually seeing the response in engine RPM. We should be experienced to move to full throttle in a smooth but brisk fashion, using only the load valve to prevent over-revving. Therefore, it is always good to think about the shape of the engine's torque vs. RPM curve because it helps to anticipate how we need to operate the load valve.

Conclusions

To test a vehicle there are many choices for the type of dynamometer that can be used for this process. Each one has its benefits and drawbacks. This includes limitations on speed, the ability to quickly change the required load and the initial expense. At this point, our air cooled eddy current absorber offer very quick load control, moderate inertia and high specific load capacity especially in the low RPM working ranges of most industrial type engines.

The Embry-Riddle Aeronautical University EcoCAR team is interested in saving as much time as possible. Earlier, we have been testing our EcoCAR vehicle in the Daytona International Speedway. Time does not necessarily equal money for our university. However, the less amount of time spent tuning the engine for the EcoCAR results in more practice time and chances for under-designed components to break prior to attending the collegiac competition.

It is concluded that, the requirements related to dyno-lab is fulfilled and the installed eddy current chassis dynamometer with proper ventilation and safety systems is now available on university campus for testing all university front wheel drive vehicles. It will help us to do more extensive testing on all Eco Car Vehicles.

Future Recommendations

1. To test the high performance engines**,** the floor anchors and restraint straps should be able to hold more than 100 MPH. No attempt was made to hold above 80MPH vehicle while testing.
2. Adding a few more floor anchors to the sides of the dynamometer would be a preventive measure for addition safety to the vehicle and the driver.
3. To install some type of temperature probe inside the dyno pit to allow tuners to observe the temperature inside the pit. A thermostat can be hooked up to the dyno pit ventilation fans to control the temperature when it is goes above the limit.
4. It would be easier if an exhaust duct could be made on top of the dyno pit exhaust fan with a small opening on a side to excavate the dyno and engine exhaust gases to a height above the room.
5. For a fully operational chassis dynamometer it is necessary to add some accessories like Air/Fuel ratio exhaust probe pump with harness for measuring a vehicle mixture

from its tailpipe, weather station for real time automatic entry of air–temperature, barometric-pressure, and relative humidity atmospheric conditions, OBD-II interface reads engine RPM, road speed, and other diagnostic data from late model vehicles. It is easier to upgrade our dynamometer to AWD and Dual eddy current absorber configurations at any time.

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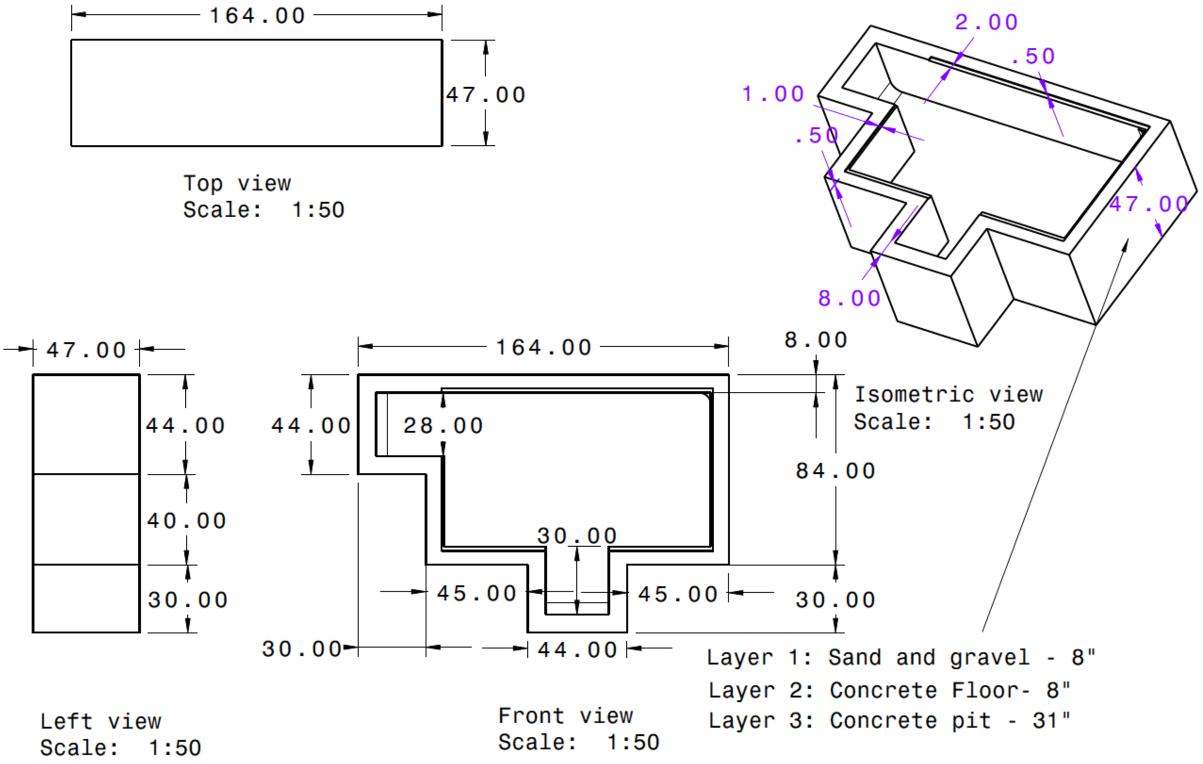
Appendix A.1

Drafting

Chassis Dynamometer pit



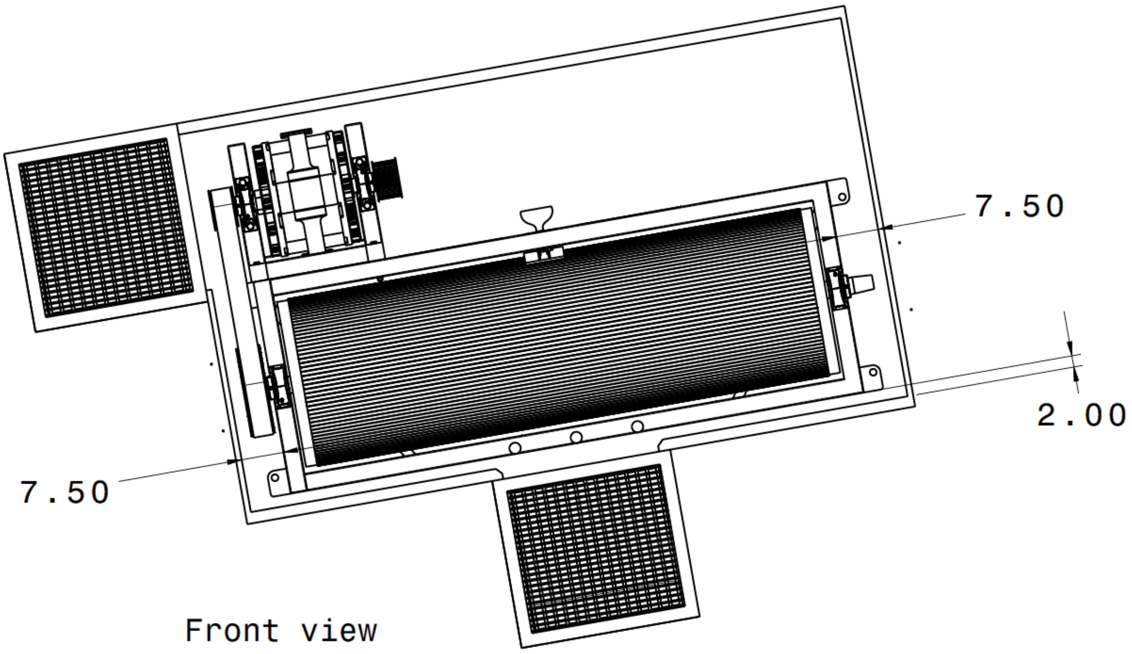
Layer 1: Sand and gravel - 8"
Layer 2: Concrete Floor- 8"
Layer 3: Concrete pit - 31"

All Dimensions are in Inches

Project	Chassis Dynamometer Pit
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	10/10/2012

Appendix A.2

Dyno pit – Dyno location



Front view
Scale: 1:20

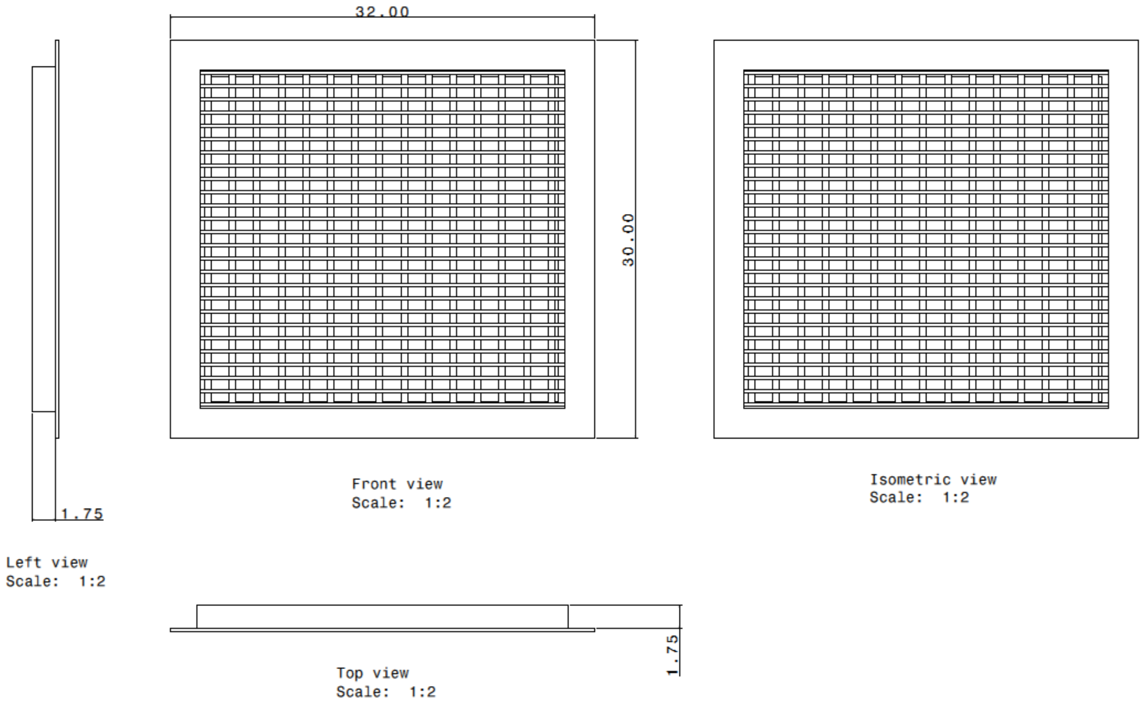
All Dimensions are in inches

Project	Dyno Pit - Dyno location
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	12/28/2012

Appendix A.3

Dynamometer parts

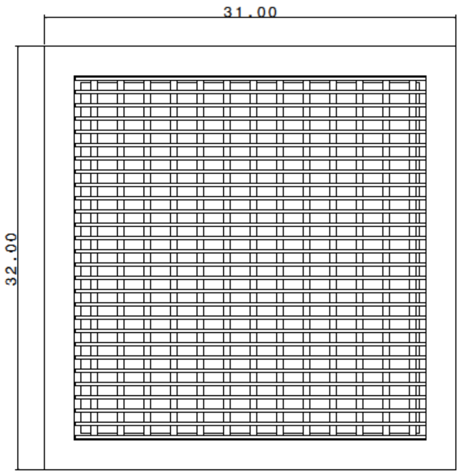
Intake Grate



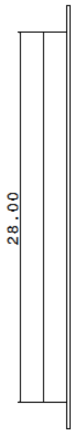
All Dimensions are in Inches

Project	Intake Grate
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	12/28/2012

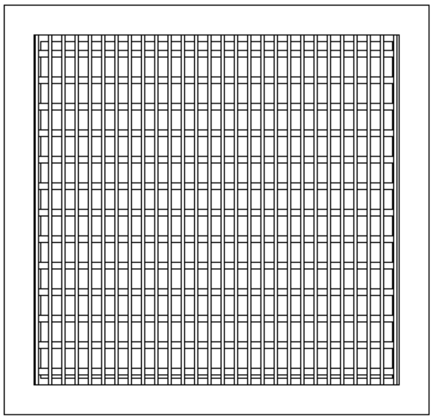
Exhaust Grate



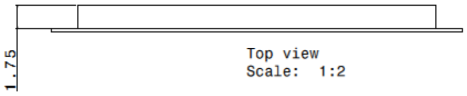
Front view
Scale: 1:2



Left view
Scale: 1:2



Isometric view
Scale: 1:2

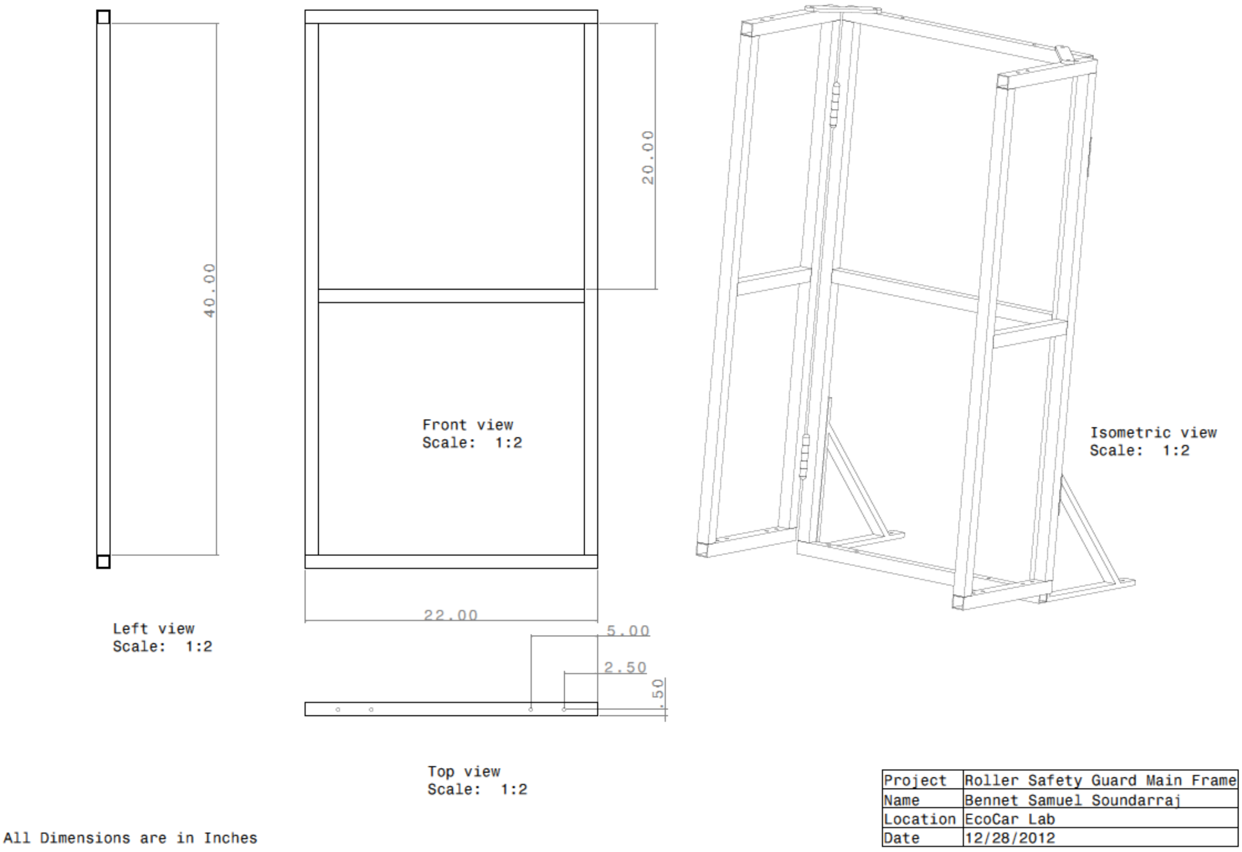


Top view
Scale: 1:2

All Dimensions are in Inches

Project	Exhaust Grate
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	12/28/2012

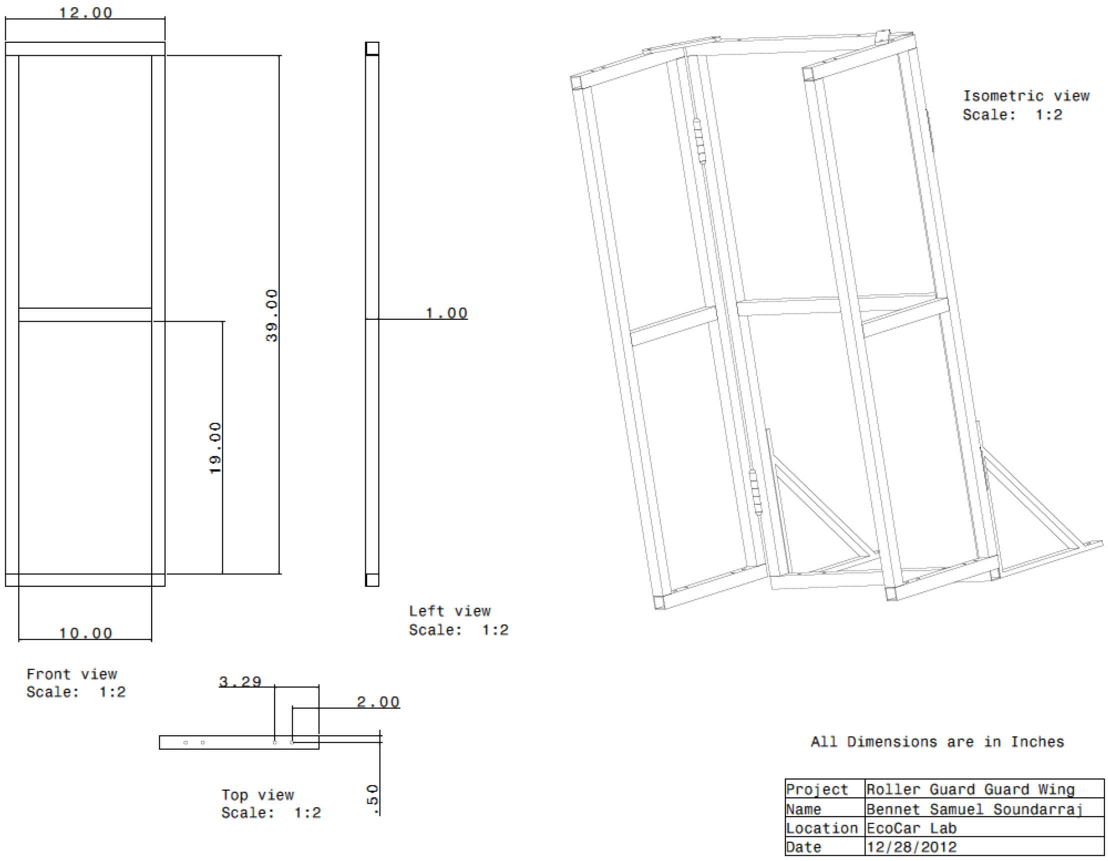
Roller Safety Guard - Main Frame



All Dimensions are in Inches

Project	Roller Safety Guard Main Frame
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	12/28/2012

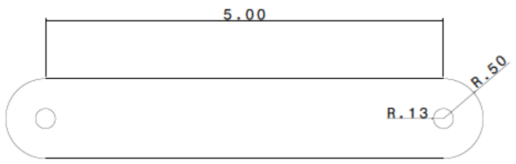
Roller Safety Guard - Wing



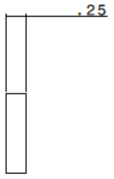
All Dimensions are in Inches

Project	Roller Guard Guard Wing
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	12/28/2012

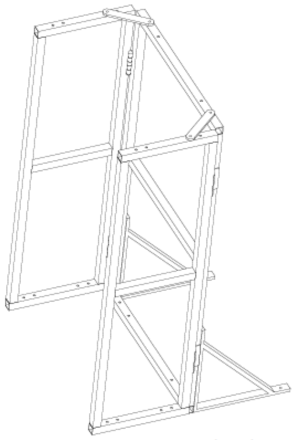
Roller Safety Guard - Stopper



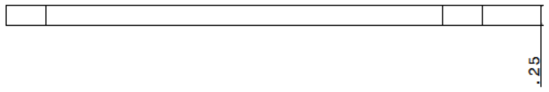
Front view
Scale: 3:1



Left view
Scale: 3:1



Isometric view
Scale: 1:3

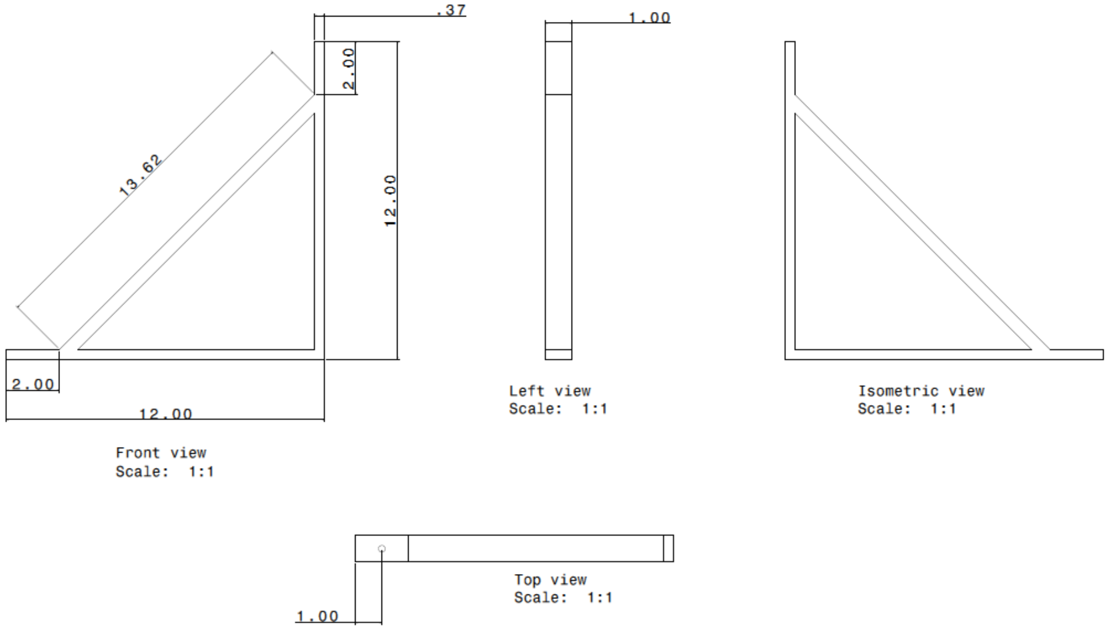


Top view
Scale: 3:1

All Dimensions are in Inches

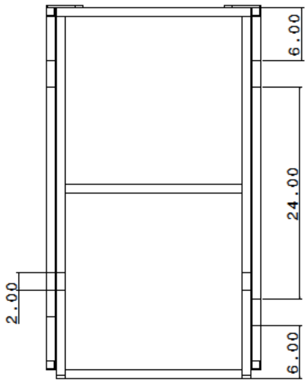
Project	Stopper Bar
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	12/28/2012

Support - Roller Safety Guard

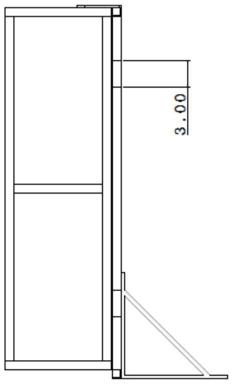


Project	Roller Safety Guard Support
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	01/10/2013

Roller Safety Guard



Front view
Scale: 1:3



Left view
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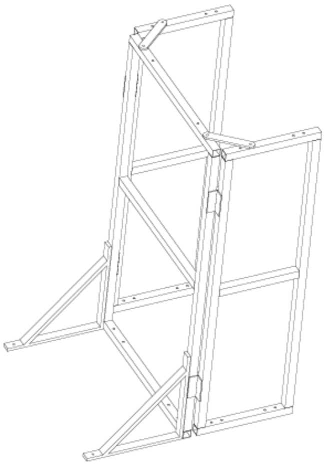
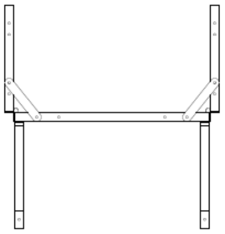


Isometric view
Scale: 1:3



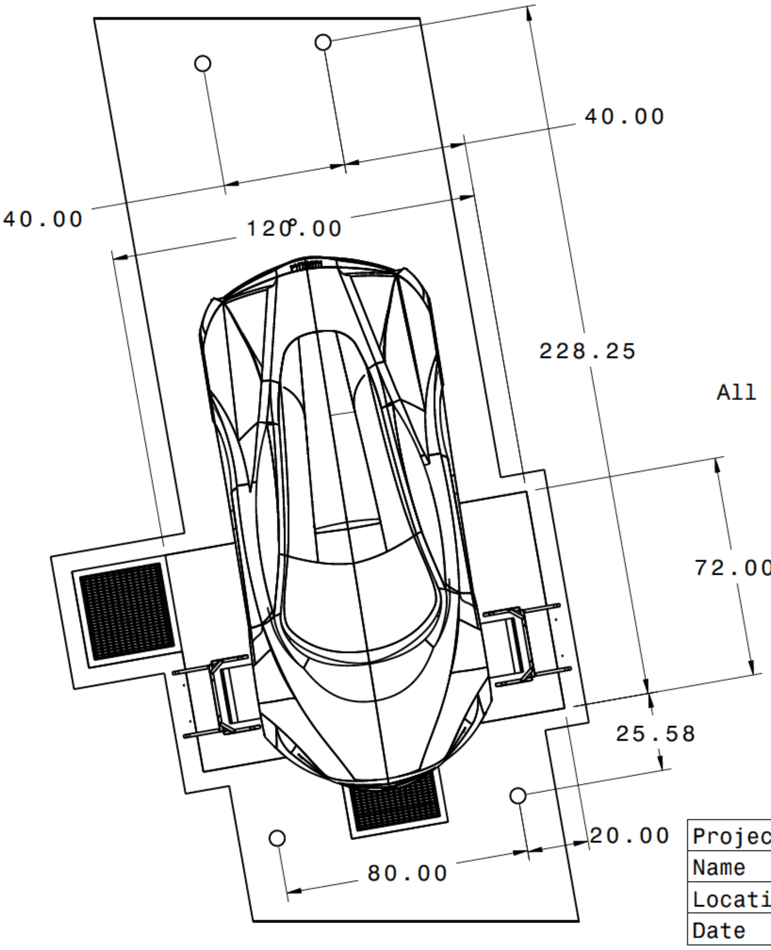
Top view
Scale: 1:3

All Dimensions are in Inches

Project	Roller Safety Guard
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	12/28/2012

Appendix A.4

Floor Anchors



Front view
Scale: 1:37

All Dimensions are in inches

Project	Floor Anchors
Name	Bennet Samuel Soundarraj
Location	EcoCar Lab
Date	12/28/2012

Appendix B

Bill of Materials

Item	**Description**	**Price Each ($)**	**Total ($)**
Dynamometer	3000 2WD EC Chassis Dyno	39,550.50	39,550.50
Supply Fan	Grainger Supply fan (7CC08)	844.00	844.00
Exhaust Fan	Grainger Exhaust fan (7CC79)	832.50	832.50
Exhauster	Grainger Fume/Smoke Exhauster (3AA20)	604.80	604.80
Mobile Fan	McMaster Direct drive mobile fan (20445K15)	500.63	500.63
Chassis Pit	AM WEIGEL CONSTRUCTION INC	21,971.00	21,971.00
Exhaust Hose	McMaster-CARR exhaust hose (5398K13)	132.48	132.48
Duct Hose	McMaster-CARR Crushproof duct hose (5398K19)	33.40	33.40
Anchors	McMaster-CARR Internally threaded anchors (97083A330)	13.14	26.28
Tool	McMaster-CARR Anchor installation tool (97077A330)	4.80	4.80
Hinges	McMaster-CARR Hinges (16175A23)	5.01	40.08
Screws	McMaster-CARR Screws (9125A714)	5.81	11.62
Steel Tubing	ALRO Metals Wall Tubing (13001524)	20.98	83.92
Expanded Sheet	ALRO Metals flat expanded metal (12001800)	107.12	107.12
Wing Nut	McMaster-CARR Wing nut (90876A366))	3.60	14.40
Thumb Screw	McMaster-CARR Spade head thumb screw (97008A825)	11.46	45.84
Duct Adapters	Home Depot Duct adapter set	35.79	35.79
Spray Paint	Home Depot Spray paint	16.74	16.74
RS232 Cable	Amazon - RS232 Cable	19.76	19.76
Grates	Metals Depot Grates materials	835.69	835.69
Total			65711.35

Appendix C

Standard Operating Procedure

EcoEagles EMBRY-RIDDLE Aeronautical University DAYTONA BEACH, FLORIDA	**ERAU - Eco Eagles** **Eddy Current Chassis Dynamometer Testing**		**Pg. 1 of 4**
	Doc Number: SOP-05.00	**Rev: Original**	

1. PURPOSE

This Standard Operating Procedure (SOP) describes the guidelines for the general use and care of Dynamometer in the EcoCar Lab #186.

2. SCOPE

This SOP is a mandatory document and shall be implemented by all employees and contractors when in the EcoCar Lab #186.

3. DEFINITIONS

An instrument, which measures the motor’s performance by creating a load using an eddy current absorber

4. RESPONSIBILITIES

- Marc Compere – EcoCar 2 Faculty Advisor
- Bill Russo – Machine shop
- Chester – Team Lead

5. TRAINING

The Team Leads are responsible for ensuring that team members who follow this procedure understand the SOP’s objectives and other inter-related activities.

6. PRECAUTIONS

Use this SOP in conjunction with SOP-01.00 Shop Behavior and Access.

7. EQUIPMENT

- Vehicle
- Eddy Current Chassis Dynamometer
- Absorber Power supply
- Dynamometer wiring harness
- Safety Frames
- Vehicle Floor anchors and Tie down straps
- Inlet and Exhaust Fan
- Radiator Fan
- Exhaust Blower fan with Hose
- Data acquisition computer
- Data controller, RS 232 cable, USB cable

8. PROCEDURE

8.1 Process Flow

Step	Action
1	Make sure there is enough space around the dynamometer for the free movement and safety purpose.
2	Make sure the safety frames are properly attached to the dynamometer frame on both ends of the roller
3	Place the anchor D-ring plates on the floor, where the red head concrete anchors are located
4	Pre-test vehicle (tires, fuel, leakage) check.
4	Depress the air brake and then carefully drive a powered vehicle onto the rolls while watching Out for clearance problems with any low hanging spoilers, etc.
5	Make sure the vehicle is centered based on the roller ends and the car lift pillars
6	Park the front wheels axle parallel to the roller and the wheels on the roller with a grade
7	Place appropriate size wheel chocks around the tires remaining on the ground (or lift) while you finish hooking up the restraining straps. Wheel chocks should never be relied upon (alone) for actual testing, as the vehicle will shift off of the rolls.
8	Setup the DYNOmite data acquisition computer and configuring DYNO-MAX before continuing to operate the dynamometer
9	Setup the exhaust blower fan with hose attached to the tailpipe and leave the other end outside the room
10	Setup the Radiator cooling fan facing the vehicle
11	Switch on the Inlet and Exhaust Fan, Exhaust blower fan, Radiator fan, Room ventilation fan
12	Start the engine, release the parking brake, put the transmission into gear and gradually bring the drive wheels up to a low speed (i.e. 10 MPH) cruise. During this time, verify that the vehicle is tracking properly (repositioning as necessary) and also verify that the DYNOmite Data Acquisition System is receiving the roll's speed signal
13	Make sure the air brake is released before starting testing
14	Start the testing session, if everything is perfect
15	Inspect the condition of the straps and wheels on a frequent basis

8.1.1 Overview

Step	Action
1	Access – Outside vehicles are not allowed to use the test facility. When the vehicle is under testing a trained faculty member or a trained staff should accompany the driver.
2	No Playing with Roller and Fans– This is for vehicle testing and should not be used to have fun, which may leads to injuries to human or fan damage
3	Front wheel drive vehicles must be secured with diagonally oriented straps to prevent side wards wander
4	Install the Restraints in both the front and aft directions, as loads reverse during vehicle breaking
5	Use the air brakes to hold the rolls from turning when driving onto or off of the rolls.
6	Always keep observers clear of front/ rear of vehicles and away from roller assembly
7	Do not put the vehicle into park or reverse until the wheels stop while testing
8	Do not leave the fans unattended. It’s necessary to give breaks during testing.
9	Do not leave the absorber supply/control module unattended before and after testing. Make sure the voltage is reading zero while it’s not on test.
10	Do not allow pit temperature more than 104F
11	Power supply failure while testing - Check the Power supply/control module load value and monitor the DYNOMAX software.
12	A test must be stopped with different levels of urgency if the vehicle under test fails; the sensing or data logging fails, or if there is a safety violation and a person is in direct danger from the spinning roller. Three remedial actions with different urgency levels for stopping the test are: 1. Stop powering the vehicle and wait for the roller to come to a complete stop 2. Apply vehicle brakes to stop roller in a quick, but controlled manner 3. Apply dyno air brakes immediately along with vehicle brakes

9. APPLICABLE REFERENCES

- N/A

10. QUALITY RECORDS

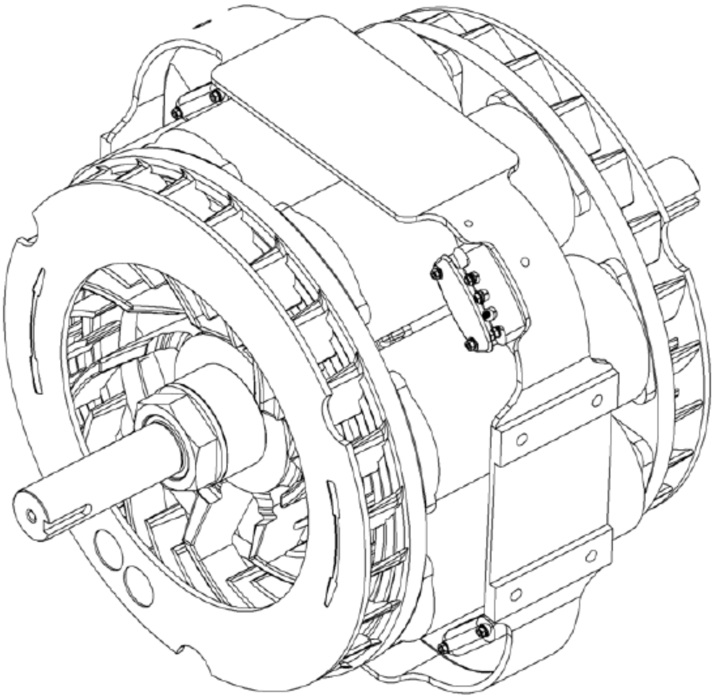
- N/A

Appendix D

Absorber Specifications

KLAM
Produced by
Industrias Zelu. S.L.

KR-250C PAU
TECHNICAL SPECIFICATIONS



POWER ABSORBER UNIT

KR-250C PAU

ST20189-rev C
AUG 2008

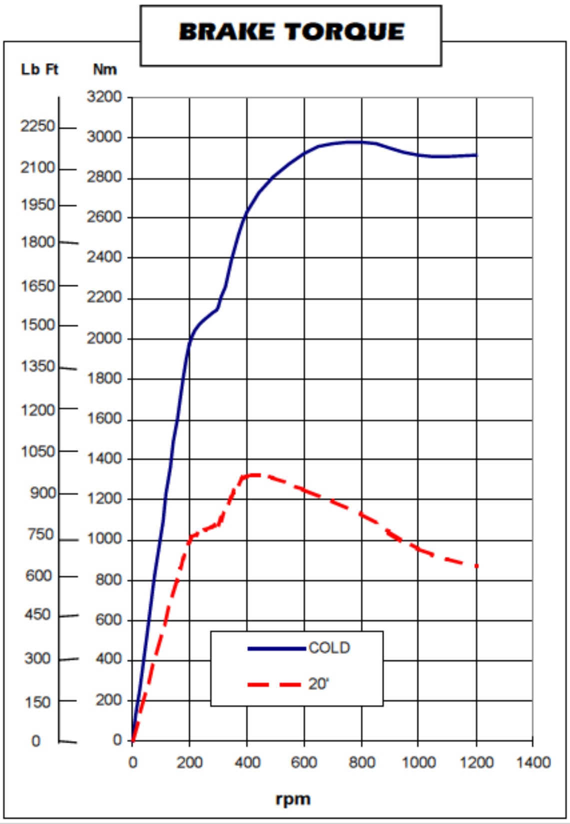
Produced by
Industrias Zelu, S.L.

KR-250C PAU
TECHNICAL SPECIFICATIONS

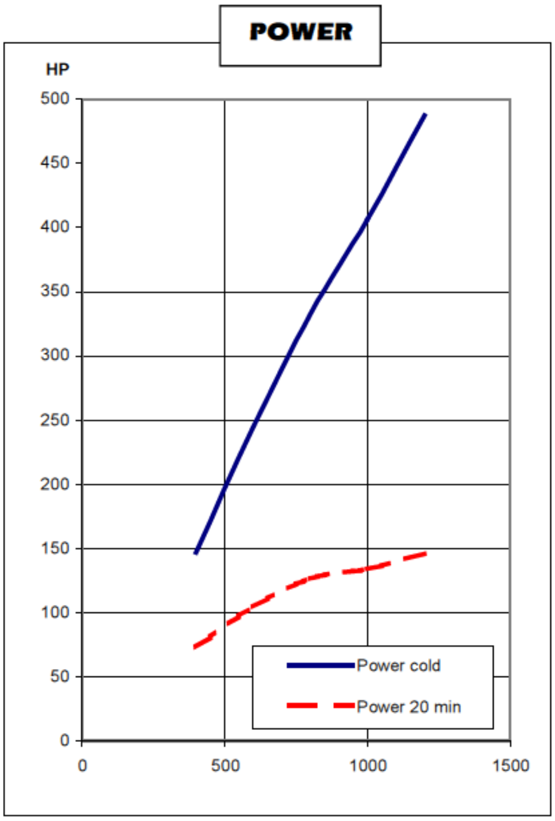
• SPECIFICATIONS

Maximum braking torque		**2970 Nm / 2190 Lb-ft**
WEIGHT	Complete	**422.5 Kg / 931.44 Lb**
	Stator	**328.5 Kg / 724.21 Lb**
	Rotors	**94 Kg / 207.23 Lb**
Rotors Inertia		**2.915 Kgm^2 / 69.23 Lb-ft^2**
Maximum transmissible torque		**31600 Nm / 23305.75 Lb-ft**
Max. admissible R.P.M. (min^{-1})	Constant Intermittent	**4800** **5300**
Air-gap regulation (±0.1 mm /±0.0039inch)		**1.4 mm / 0.0551 inch**

• PERFORMANCE CURVES



BRAKE TORQUE

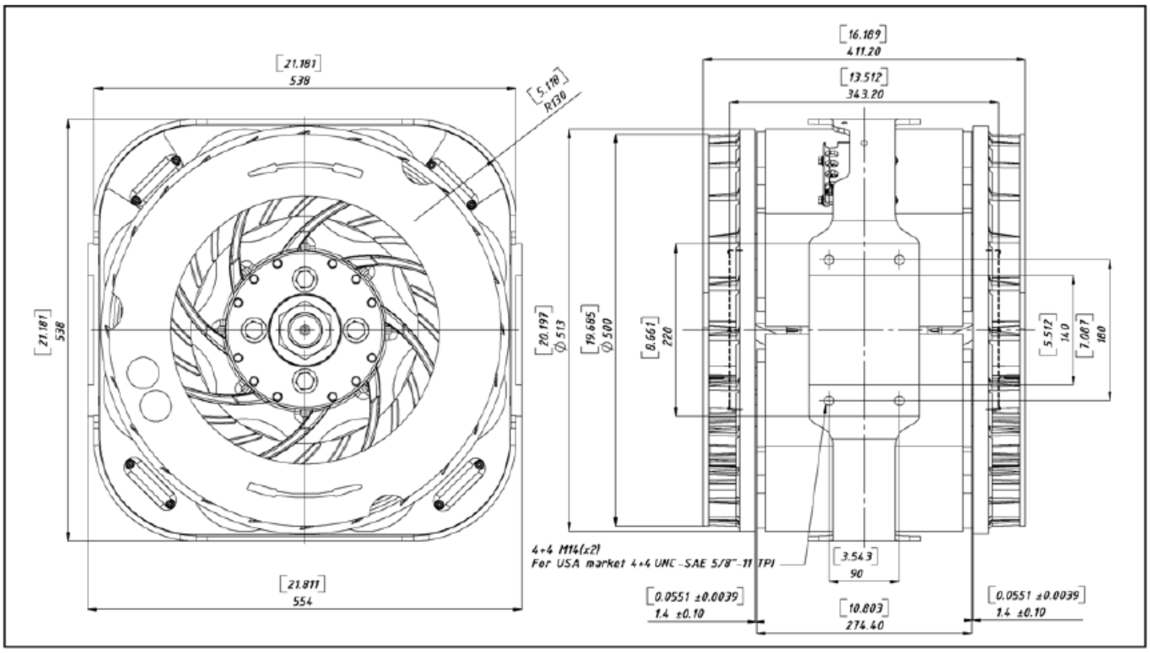


POWER

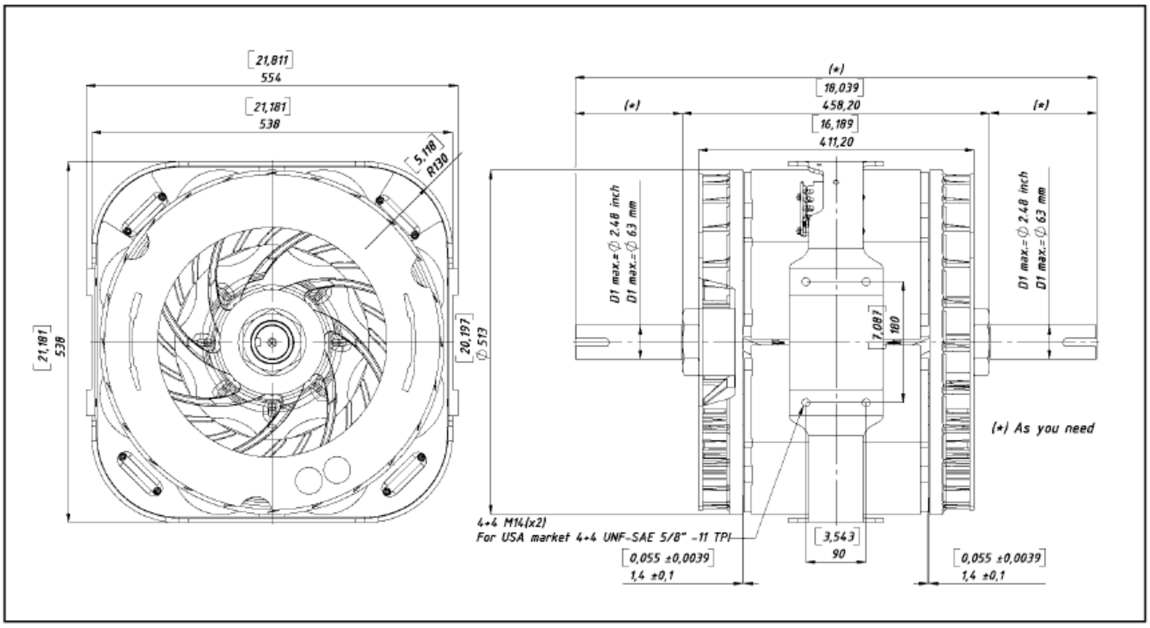
Produced by
Industrias Zelu, S.L.

KR-250C PAU
TECHNICAL SPECIFICATIONS

- **DIMENSIONS With SAE 1800 flanges. [inches] mm**

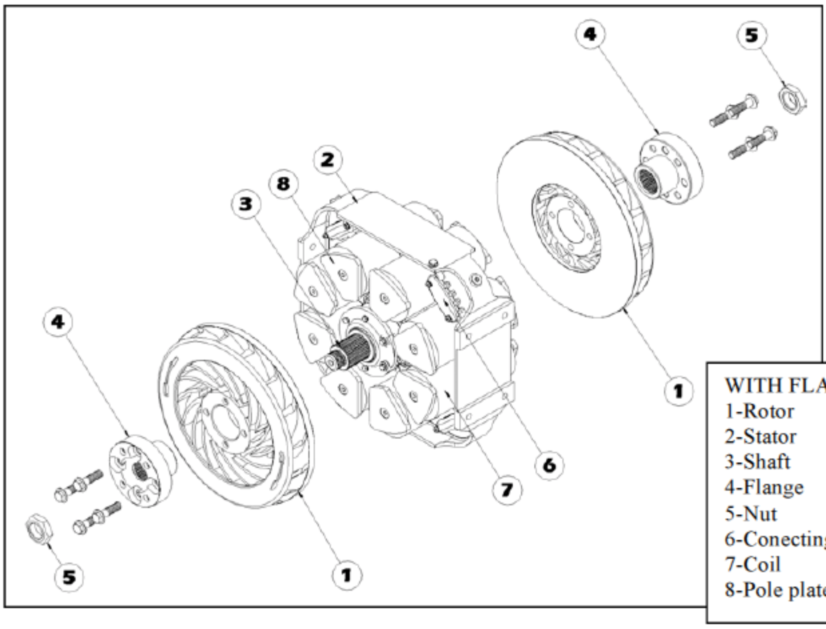


- **DIMENSIONS With extended shaft. [inches] mm**

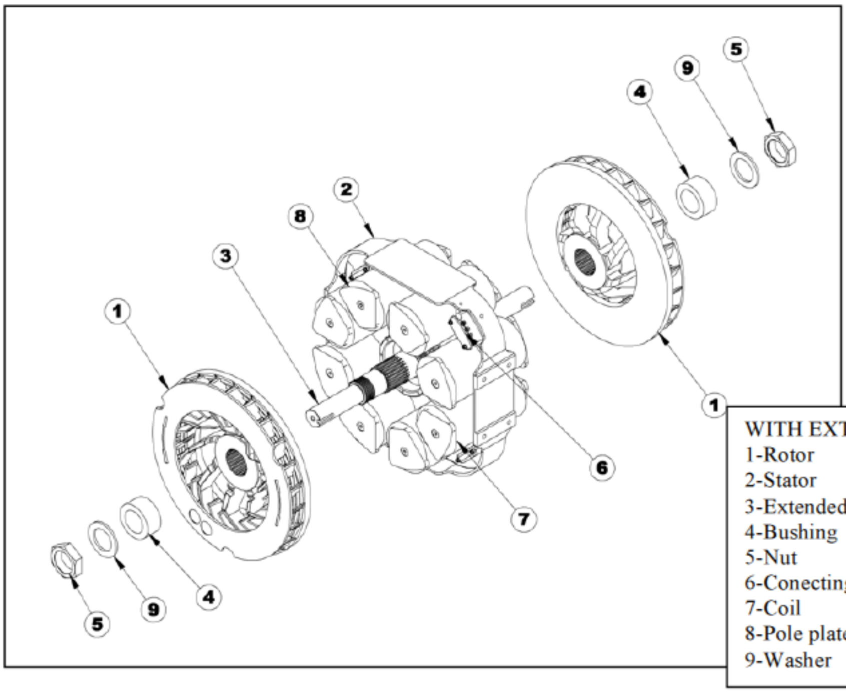


The dimensions of the shaft are defined by the customer

- **MAIN COMPONENTS**



WITH FLANGE
1-Rotor
2-Stator
3-Shaft
4-Flange
5-Nut
6-Conecting terminal
7-Coil
8-Pole plate



WITH EXTENDED SHAFT
1-Rotor
2-Stator
3-Extended shaft
4-Bushing
5-Nut
6-Conecting terminal
7-Coil
8-Pole plate
9-Washer

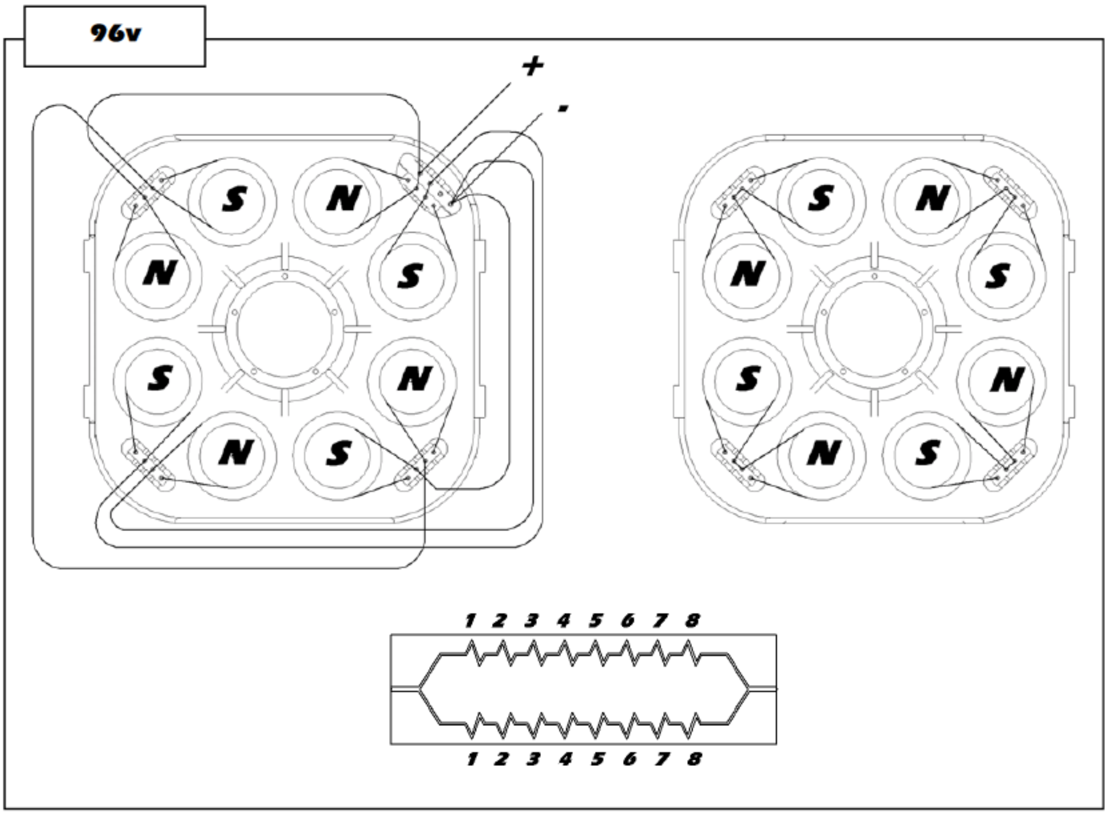
KR-250C PAU
TECHNICAL SPECIFICATIONS

• ELECTRICAL SPECIFICATIONS

Voltage *	**96 V**
Resistance per coil (Ω) ±5% (20°C)	**0.66**
Resistance (Ω) ±5% (20°C)	**2.64**
Consumption (A) ±5% (20°C)	**36**
Insulation resistance (MΩ)	**1**

*ALSO AVAILABLE IN DIFFERENT VOLTAGES (LIKE 12,24,48,76 OR 192 VDC).
BE ADVISED THAT BRAKE TORQUE AND BRAKE POWER WILL CHANGE

• INTERNAL WIRING DIAGRAM



KLAM

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