Experimental study of energy efficiency of a hydraulic system

Abstract: Energy efficiency in products and processes is essential for sustainable future of an advanced society. Because of the complexity of theoretical model of energy loss in a system, traditionally, energy efficiency goal is achieved by studying the performance of an existing system and then modifying its design. As part of a design process, an experimental method is prescribed for understanding the nature of energy loss. Use of the experimental result in the design process can result in significant benefit in achieving the sustainability objectives of a product or process. Development of the prototype of a class of product will required flexibility in the use of laboratory equipment. A modular form of laboratory is utilized to develop the prototype of a hydraulic system. These are power, flow, load, conditioning, instrumentation and external modules. The modules can be combined to create the prototype of a hydraulic system and study its performance as necessary. The prototype performance data will be used in design process to optimize the design and achieve its energy efficiency goals as part of routine design process.

1. Introduction

Worldwide, the vast majority of energy is produced from fossil-based fuels resulting in the increase of carbon dioxide in the atmosphere [1]. In the area of fluid power, United States consumes about 2 Quads of energy per year with an average of 22% system efficiency [2]. The design of industrial products and processes requiring less energy will significantly impact the demand of fossil fuel-based energy and its impact on climate. Production of 2 Quad energy costs about \$60B, in process emits 360 million metric tons (MMT) of CO_2 to the atmosphere each year. Improving this efficiency by just 5% would save fluid power industry about \$10B per year, reducing CO_2 emission by 66 MMT. A 10% improvement will bring the energy efficiency of fluid power system comparable to that of internal combustion engine, saving the industry \$20B per year and reducing yearly CO_2 emission by 110 MMT. Considering this benefit, industries are looking for methods to reduce overall energy consumption and maximize sustainability of products and processes. Achieving this goal is a complex gradual process and requires a different design methodology. In academia, this awareness has led to various curriculum reform with the goal of enabling programs graduates to lead these changes in professional practice. It is essential to understand the source and nature of a problem prior to design of a system. The National

Science Foundation funded various projects to update engineering curriculum for the comprehensive teaching of energy in different undergraduate programs. NSF funded Accelerated testing methodology project [3] utilized statistical method to determine the interrelationship between various stress loadings and total energy use in a mechanical system. This established a framework to facilitate the optimum experimental design and energy reduction in the process. The US Department of Energy promotes best practices in energy efficiency, reusable energy, waste reduction, and productivity improvement through the integration of activities. While energy efficiency and conservation is a novel objective on its own merit, many consider this essential for long term sustainability of an industrial society [4, 5, 6]. Generally, engineering design classes in undergraduate programs follow a structured problem- solving approach for solutions of open ended design problems. Besides achieving mechanical integrity of the product and intended product functions, additional analysis tools are utilized to achieve other design goals, typically referred to as design for X [7]. This includes a variety of design objectives to ensure long term sustainability of products and processes. Design for Environment (DfE), or ecodesign [8, 9] aims to reduce the environmental impact in the life cycle of a product by enhancing its design objectives. It may also aim to reduce resource consumption, in terms of material, energy, and pollution prevention. Other concepts, such as Design for Disassembly (DfD) and Design for Recycling (DfR) practices [10, 11, 12], would also allow the product designer to have a substantial positive impact on the environmental aspects of a product's lifecycle.

This paper presents an approach that utilizes energy efficiency characteristics of a fluid power system in system design. Because of the analytical complexity of the subject, an experimental method is utilized to improve the energy efficiency of the system in its normal operating conditions. Though the methodology is used in a typical capstone design project, it can be beneficial for design of a mechanical system in general.

2. Energy efficiency and design process

Understanding of energy loss in the overall system is essential for design of a hydraulic system with the goal of improving its energy efficiency. Analytical formulation of overall energy efficiency in a system is complex and detail analysis of the problem is not expected within the reach of most undergraduate level student groups. This problem can be addressed by studying the behavior of a prototype system in the laboratory and utilizing the result to improve the design and minimize energy loss in the system. Though the goal of the study is to optimize energy efficiency of a hydraulic system, a design project is limited by scopes. Therefore, it is essential to establish a realistic goal of the study prior to any experimentation.

The experimental process would start with the development of a laboratory prototype. It would be developed according to system specification in a conventional design. Prototype would be scaled to fit the laboratory limitations if such scaling does not affect characteristics of the system significantly. Such development also includes additional instrumentation and data acquisition for detailed monitoring of process behavior. The prototype would be tested in the laboratory to check its function and process behavior according to the design. Major sources of energy loss in a hydraulic system is well known. Once the process behavior is verified, energy losses in the prototype system would be measured and tabulated as a routine process. Often common sense practices can be adapted to enhance energy efficiency without formal design changes. Next phase of the experimental process is operation of the system under variety of conditions and acquiring of process data. A nonlinear regression modeling method is utilized to fit the process behavior with their analytical nature. Upon performance of sensitivity analysis of process data, parameters most effecting energy efficiency of the overall system is identified. Result of this analysis leads a designer to innovative solutions of a design problem. In this paper, example of an experimental analysis to improve energy efficiency of a human powered hydraulic transportation system is presented.

It is a conventional capstone design project, where a group of students are assigned a two semester design project. They go through routine step by step process of problem definition, concept generation, design analysis, design specification, component selection and fabrication, prototype development, performance testing, and validation of the design process. The student group is assigned to design a human powered hydraulic system capable of transporting a single person. Without using any direct drive mechanism, the system should be able to transfer the rider's power to the driving wheel through the use of a hydraulic system. The system should also be able to capture energy lost due to braking or downhill motion and store it for later use. In this type of project, after design analysis students would select standard components available commercially and fabricate all nonstandard components. The system would be assembled and tested for its performance. The most challenging part of this design has been optimizing the energy efficiency of the system. The most significant sources of energy loss in this system are the hydraulic pumps and motors. Based on their performance requirement, all commercially available models are selected. Manufacturers of the components provide performance characteristics tested in their normal range of operating conditions. In this design project, components operate in much broader range of operating conditions, therefore, their performance beyond normal operating conditions is essential in determining overall system efficiency. Design process incorporated development of this test process and performance testing of pump and motor. Meaningful analysis of the test data requires sophisticated measurement, data acquisition, and an analysis system in the laboratory. Therefore, a new laboratory is being developed to assist student groups with such experiments.

3. Energy efficiency testing laboratory

A laboratory (Figure 1) is developed to test performance of the prototype, variety of system configuration, and a fluid power system in general. For a hands-on study of the process and the designed system, one can assemble the components, create the desired application, and study its performance. The laboratory is composed of six modules. Using quick connect coupling and a flexible hose, these modules can be connected to create the system under investigation.

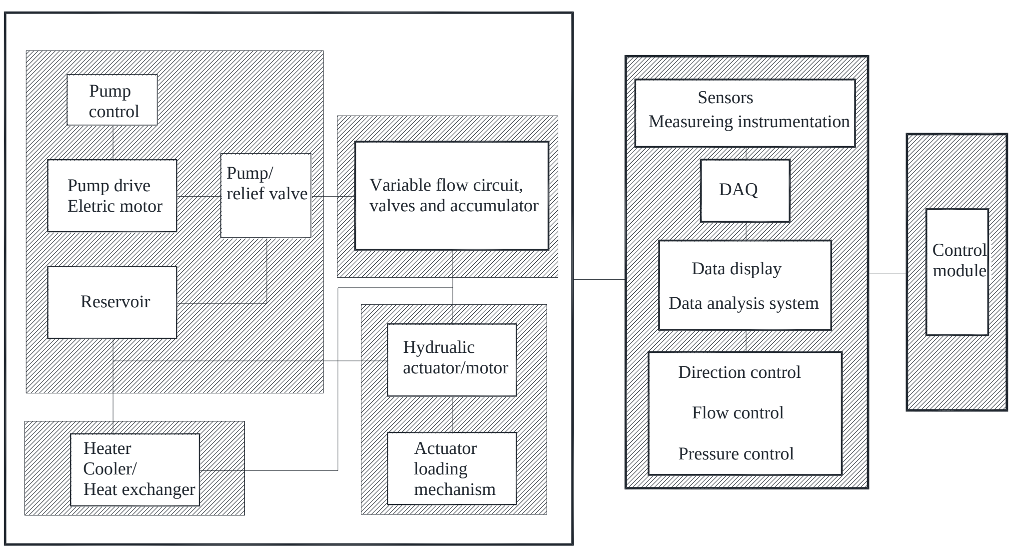

Figure 1. Layout of the test laboratory

Pump module: This module has a series of variable displacement pumps to supply a fluid power system in general. The pumps is driven by 7.5, 2 and 0.5 HP electric motors with their own control (ABB ACS 500) to vary flow rate. A 30 gallon reservoir is used to supply fluid to these pumps

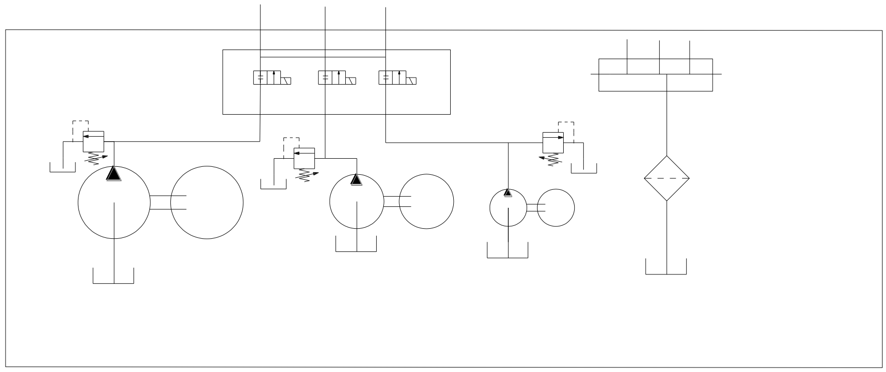

Figure 2. Pump module circuit

and other components of the module. A flexible pump mounting fixture is added to allow the installation of other pumps in a test system. A solenoid valve operated supply manifold is used to provide power from individual or combination of pumps. Flow from a hydraulic system returns to the reservoir through another manifold and cartridge filter. The whole module is mounted on a portable frame and quick connect couplings are used to integrate with other modules as necessary.

Flow and conditioning module: This module will be used to create any flow circuit necessary for a specific system under consideration. It consists of a bank of stainless steel tubes in layers which can be connected in series or parallel using two way direction control valves. One would be able to create different types of flow circuit utilizing the tubes, hoses, and direction control valves installed in the module. To ensure the maintenance of physical properties and chemical stability, hydraulic fluid from the actuator is conditioned prior to the return to the reservoir. Hydraulic fluid will be conditioned using a panel filtration unit, a heating unit and a heat exchanger in this module. This allows for testing the performance of a hydraulic system in a desired operating temperature, irrespective of ambient temperature.

Actuation module: A hydraulic motors and cylinders required in a system under investigation are installed in this module. The module has flexible mountings to allow for the installation of different hydraulic motor or cylinder. A hydraulic motor is used to drive the pump with desired torque and rpm. Motor power is supplied by the flow from the pump module. Load on the pump is created by controlling the pressure and flow rate at the pump exit.

Instrumentation module: This module has sensors, data acquisition, data processing, and a display and control instrumentation. A combined SCXI and PXI chassis based National Instrument hardware is utilized for this purpose. NI DAQ cards, such as NI PCI-7342, 6024E, GPIB ENET, NI CR10-9073, NI 9213, NI 9205, NI 9901, NI 9977, and other accessories are utilized for

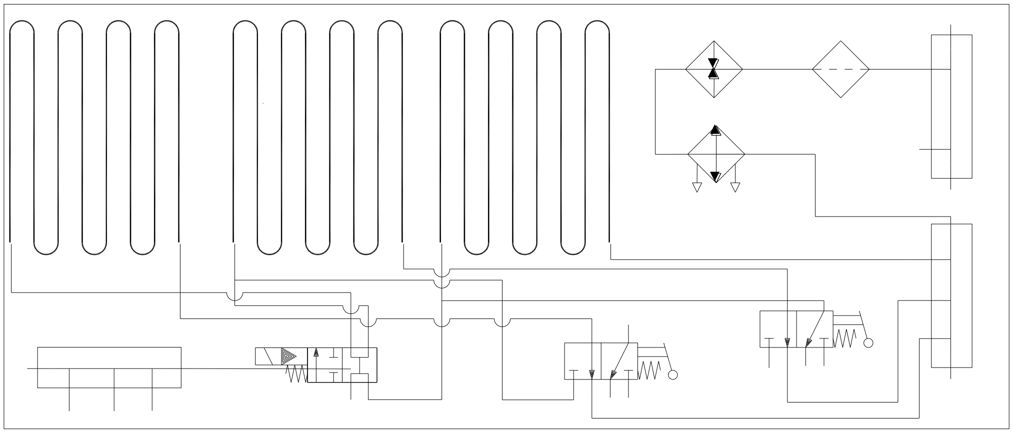

Figure 3. Flow and conditioning module

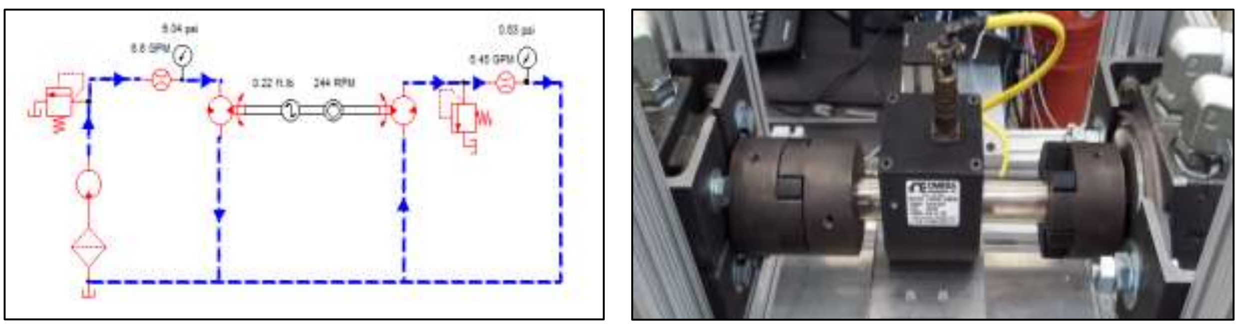

Figure 4. Actuator module and load coupling

collecting all process data (pressure, temperature, flow, torque, force, and rpm) in either analog or digital form. The sensors are configured by the DAQ modules for their excitation and output signals. The system also allows sending appropriate signals to process actuators (valves, pump drive and temperature controller). LabVIEW program is utilized to integrate the process sensors with the analysis and control system. Additionally, Matlab, Automation Studio, and other analysis tools are used for further study of process and component behavior based on the data acquired.

Control module: This is an external module that uses mainly microcontrollers and programmable logic controllers (PLCs) in fluid power process. It replicates a hardware-based control systems, as opposed to the software-based controls included in the Instrumentation Module. It can be expanded to control other systems besides the fluid power modules, thus allowing for a wider range of possible projects.

4. Experimental analysis

The objective was to design a hydraulic system that would minimize energy loss and optimize performance of the system in a series of competitive races meeting specified performance criteria. This required the overall system is developed using the most energy efficient components available at the operating conditions of the races. In the system, efficiency of the hydraulic pumps and hydraulic motors were the most important factors. A test cell (Figure 1) was developed and performance data of the pumps and motors were acquired using a LabVIEW program. The data was imported in Excel for detailed analysis.

Energy efficiency mapping: In the design process, two sets of pumps and motors were selected and are identified as "Aerospace" and "H3" in all test results. The purpose of the test was to determine which pump and motor would operate at higher efficiency during the duration of the races. Based on the desired speed of the bike in race track, shaft rpm of pump and motor was determined as function of time. Table 1 shows the bike speed, corresponding track length, shaft rpm and its duration. The data is used to calculate *Speed Factor* at each pump and motor shaft speed as fraction of total race time. $S_i = \frac{t_i}{T}$ … (1)

Where, S_i = Speed Factor

t_i = Duration of speed and

T= Duration of the race.

Corresponding shaft speed is calculated based on wheel rpm and gear ratio.

In the laboratory efficiency characteristics of the pumps and motors are mapped with respect to shaft rpm and pressure (Figures 5 and 6). Rotational speed and power are measured by utilizing an electric motor control system. Appropriate pressure and flow is maintained by using a pressure relief valve and a flow control valve.

Using the efficiency maps of the pump and motor, an overall *Efficiency Index* is calculated for both sets of pump and motor. Efficiency Index at each shaft speed is given by:

$$E_i = S_i \eta_i \quad \dots (2)$$

Where, E_i = Efficiency Index

η_i = Efficiency at pressure i

Overall *Efficiency Index* is $E = \sum_{i-1,n} \sum_{j=1,m} E_{ij}$ … (3)

1 Lap												
	Start	Length 1	Turn 1	Length 2	Turn 2	Length 3	Turn 3	Length 4	Turn 4	Length 5	Turn 5	Total
Length(ft)	100	4400	100	2000	200	2800	150	1200	150	2400	942.4778	14442.48
Speed (mph)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)
5	2	0	1	0	6	0	4	0	4	0	4	21
10	2	0	3	0	5	0	3	0	3	0	24	40
15	2	14	4	6	4	9.5	3	4	3	8.2	8	65.7
20	2	84	0	36	0	57	0	24	0	49.2	4	256.2
25	0	28	0	12	0	19	0	8	0	16.4	0	83.4
30	0	14	0	6	0	9.5	0	4	0	8.2	0	41.7
T (s)	8	140	8	60	15	95	10	40	10	82	40	508
Time	8.46667	Min										
Speed (mph)	Factor	RPM @ Wheel										
5	0.0413	64.98242001										
10	0.0787	129.96484										
15	0.1293	194.94726										
20	0.5043	259.92968										
25	0.1642	324.9121001										
30	0.0821	389.8945201										

Table 1. Speed factor

Where i and j are for each pressure and speed factor

For overall calculation speed and efficiency data was used to create regression model of efficiency characteristics and calculate efficiency index for any shaft speed and pressure in a specific design scenario. The result of the analysis are shown in Table 2 and 3. Based on this analysis highest efficiency index pump and motor were found to be 154.441 and 197.9571 for the Aerospace pump and motor respectively.

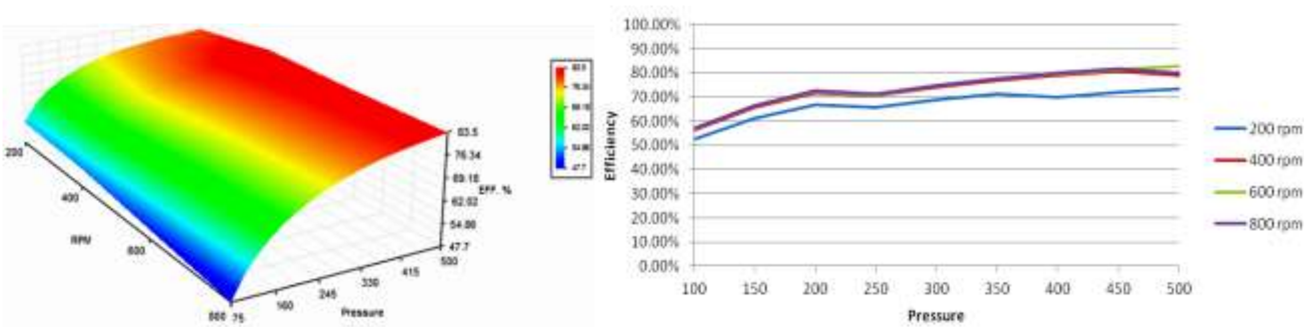

Figure 5. Efficiency mapping of an axial piston pump

Therefore, they were chosen in the final design. In a later stage of the design, efficiency index formulation was modified introducing factors due to size, weight and cost of pumps and motors.

Because of low cost, H3 pump and motor were deemed more suitable in final component selection.

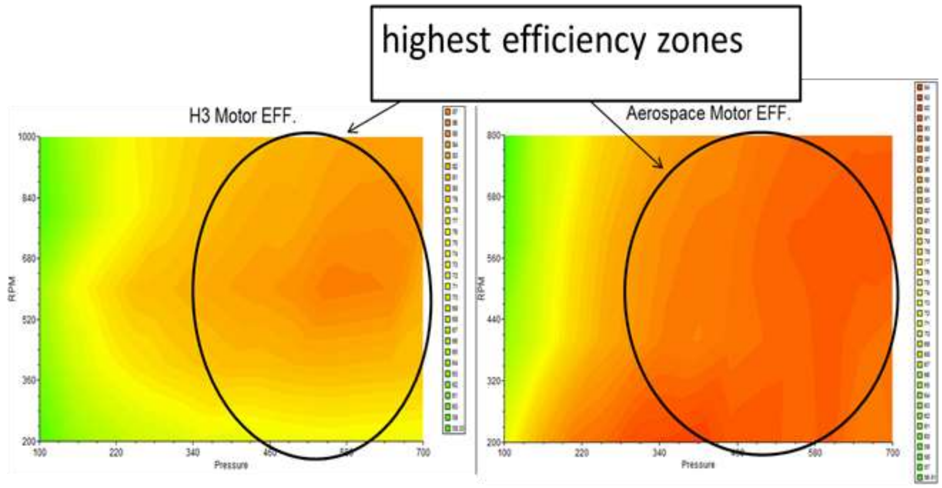

Figure 6. Efficiency mapping of two hydraulic motors.

Aerospace												
Speed (mph)	Factor	RPM	Pump Efficiency Map					Point				
5	0.0413	64.98242	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
10	0.0787	129.9648	0.5053	0.6449	0.6676	0.6403	0.7053	2.089	2.666	2.760	2.647	2.916
15	0.1293	194.9473	0.5152	0.6566	0.6784	0.6702	0.7202	4.057	5.170	5.342	5.277	5.671
20	0.5043	259.9297	0.5251	0.6683	0.6892	0.7001	0.7351	6.791	8.643	8.913	9.054	9.507
25	0.1642	324.9121	0.535	0.68	0.7	0.73	0.75	26.982	34.294	35.303	36.816	37.825
30	0.0821	389.8945	0.55	0.7	0.72	0.76	0.77	9.030	11.492	11.820	12.477	12.641
Weight factor	Cost		0.5645	0.7184	0.7409	0.7903	0.7903	4.634	5.897	6.082	6.487	6.487
2	11										Total:	154.441

H3												
Speed (mph)	Factor	RPM	Pump Efficiency Map					Point				
5	0.0413	64.98242	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
10	0.0787	129.9648	0.611	0.711	0.749	0.795	0.785	2.526	2.939	3.096	3.286	3.245
15	0.1293	194.9473	0.611	0.714	0.756	0.79	0.79	4.811	5.622	5.953	6.220	6.220
20	0.5043	259.9297	0.611	0.717	0.763	0.785	0.795	7.902	9.273	9.868	10.152	10.282
25	0.1642	324.9121	0.611	0.72	0.77	0.78	0.8	30.815	36.312	38.833	39.338	40.346
30	0.0821	389.8945	0.61	0.72	0.78	0.79	0.815	10.015	11.820	12.806	12.970	13.380
Weight factor	Cost		0.606	0.737	0.789	0.819	0.8335	4.974	6.050	6.477	6.723	6.842
3	10										Total:	123.032

Table 2. Pump Efficiency Index

Aerospace			Motor Efficiency Map					Point				
Speed (mph)	Factor	RPM @ motor	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
5	0.0413	64.98242001	0.78	0.885	0.944	0.947	0.923	3.2244	3.6585	3.9024	3.9148	3.8156
10	0.0787	129.96484	0.76	0.883	0.936	0.944	0.922	5.9843	6.9528	7.3701	7.4331	7.2598
15	0.1293	194.94726	0.74	0.881	0.928	0.941	0.921	9.5705	11.3940	12.0019	12.1700	11.9114
20	0.5043	259.92968	0.72	0.879	0.92	0.938	0.92	36.3118	44.3307	46.3984	47.3062	46.3984
25	0.1642	324.9121001	0.7	0.877	0.912	0.935	0.919	11.4921	14.3980	14.9726	15.3502	15.0875
30	0.0821	389.8945201	0.661	0.7895	0.86	0.798	0.899	5.4259	6.4807	7.0594	6.5505	7.3796
Weight factor	Cost										Total:	197.9571
2	11											

H3			Motor Efficiency Map					Point				
Speed (mph)	Factor	RPM @ motor	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
5	0.0413	64.98242001	0.56	0.64	0.67	0.69	0.7	2.3150	2.6457	2.7697	2.8524	2.8937
10	0.0787	129.96484	0.57	0.66	0.69	0.71	0.72	4.4882	5.1969	5.4331	5.5906	5.6693
15	0.1293	194.94726	0.58	0.68	0.71	0.73	0.74	7.5012	8.7945	9.1825	9.4411	9.5705
20	0.5043	259.92968	0.59	0.7	0.73	0.75	0.76	29.7555	35.3031	36.8161	37.8248	38.3291
25	0.1642	324.9121001	0.61	0.72	0.76	0.78	0.78	10.0146	11.8205	12.4772	12.8055	12.8055
30	0.0821	389.8945201	0.635	0.749	0.789	0.813	0.819	5.2125	6.1483	6.4766	6.6736	6.7229
Weight factor	Cost										Total:	117.8433
3	10					Gear at back 1:1						

Table 3. Motor Efficiency Index

5. Conclusion

An experimental analysis method for design of an energy efficient system is presented. Example of such analysis in design of a hydraulic transportation system is presented. Gathering of the experimental data and its analysis is integrated with the design process. The result was a superior design and better realization of design objectives. The methodology can be applied in achieving energy efficiency in design process in general.

Bibliography

1. Energy in the United States, Wikipedia, **http://en.wikipedia.org/wiki/Energy in the United States**
2. Estimating the Impact (Energy, Emission and Economics) of the U. S. Fluid Power Industry, Oak Ridge National Laboratory report, ORNL/TM-2011/14, 2012.
3. Liao, H.T. and Zhang, D.. "Statistically Precise and Energy Efficient Accelerated Life Testing," *SAE Int. J. Mater. Manuf.*, v.4, 2011, p. 992-998.
4. Foundation for Global Sustainability, *Do You Know What Sustainability Mean?*, http://www.kornet.org/fgs/edu/index.html
5. Robert A. Frosch, “Sustainability Engineering (editorial)”, *The Bridge* 29:1, Spring 1999

6. UN Environment Program/Industry and Environment, *Ecodesign: A promising approach to sustainable production and consumption*. Tech. Rep. CP18, 1997
7. Timkor, S., Haapala, K. and Kumar, V.; *New Engineering Design Concepts for Sustainable Products*, Proceedings of ASEE Annual conference and Exhibition, 2006.
8. Design for Environment (DfE) or Ecodesign Definition, **http://www.dantes.info/Projectinformation/Glossary/Glossary.html**, 2006.
9. Hollowayu, L., *Materials selection for optimal environmental impact in mechanical design*, Materials and Design, pp.133-143, 1998.
10. Gungor, A., Gupta, S. M., *Issues in environmentally conscious manufacturing and product recovery: a survey*, Computers & Industrial Engineering, 36, pp. 811-853, 1999.
11. Burke, D., K. Beiter and K. Ishii, *Life cycle design for recyclability*, Proceedings of the ASME Design Theory and Methodology Conference, Scottsdale, AZ, 1992, DE-42, pp. 325– 332.
12. Ishii, K. Charles F. Eubanks and Patrick Di Marco, *Design for product retirement and material life cycle*, Materials and Design, 5, pp. 225–233. 1994.