Proceedings of the 2011 powertrain systems and design student conference

Andrew Baglio
Caroline Bills
Jefferey Bird
Charles O'Neill, Matthew Borton

Follow this and additional works at: https://scholarworks.rit.edu/other

Recommended Citation
Baglio, Andrew; Bills, Caroline; Bird, Jefferey; and Borton, Charles O'Neill, Matthew, 'Proceedings of the 2011 powertrain systems and design student conference' (2011). Accessed from https://scholarworks.rit.edu/other/691

This Conference Paper is brought to you for free and open access by the Faculty & Staff Scholarship at RIT Scholar Works. It has been accepted for inclusion in Presentations and other scholarship by an authorized administrator of RIT Scholar Works. For more information, please contact ritscholarworks@rit.edu.
During the spring quarter of the 2010-11 academic year at RIT, students participated in a technical elective course on powertrain systems and design. A series of guest lecturers presented materials on a wide variety of modern powertrain topics such as basic theory of gearing, power transmission, hydraulics, and electro-mechanical actuation, automotive applications, aerospace applications, gear manufacturing processes, and emerging markets and technologies in powertrain systems and technologies.

Each student identified a topic of personal interest in the field of powertrain systems and design, and prepared a technical paper on their chosen topic. These papers were presented in a conference at the conclusion of the course, and the papers resulting from the student investigations are assembled herein.

Professor: Dr. Edward Hensel, PE

Acknowledgements

The contributions of the following individual is gratefully acknowledged. Their presentations and introductions to modern powertrain systems and design topics is appreciated.

Hydraulic Pump: Scott Shafer, Moog Inc.
Automotive Powertrain Applications: Stephen Boedo, RIT
Electromechanical Actuators: Ken May, Moog Inc.
Planetary Gearing: Chris Layer, Moog Inc.
Electric Motor Application: Jon Culkowski, Moog Inc.
Cylindrical Gear Basic: Thomas J. "Buzz" Maiuri, The Gleason Works
Bevel Gear Analysis and Optimization: Mohsen Kolivand, The Gleason Works
Hydraulic Actuatio: Mike Ercolano, Moog Inc.
Powertrain Implications of PEM Fuel Cell Vehicles: Jason Kolodziej, RIT
Contents

Author                  Title

Andrew Baglio          M1 ABRAMS MAIN BATTLE TANK
Caroline Bills         HYDRAULIC TRANSMISSIONS
Jeffrey Bird           CNC VERTICAL MILL
Charles Borton         DRIVETRAIN THEORY AND OPERATION FOR USE IN BAJA SAE COMPETITIONS
Iric Bressler, Jr      MODERN GEAR MANUFACTURING
Conley Brodziak       THEORY AND OPERATION OF PROTON EXCHANGE MEMBRANE FUEL CELLS
Philipp Buchling Rego  THEORY AND OPERATION OF A TWO-MODE HYBRID ELECTRO-MECHANICAL TRANSMISSION
Jeffrey Chiappone      ANALYSIS AND FORECAST OF OPERATIONS AT GM’S TONAWANDA POWERTRAIN FACILITY
Dylan Connole          HORIZONTAL AXIS WIND TURBINE POWERTRAINS
Matthew DeRosa         FLYWHEEL KINETIC ENERGY STORAGE
Matthew Garafolo       THEORY AND OPERATION OF AUTOMOTIVE PEM FUEL CELL POWERTRAITS
Masoud Golshadi        THEORY AND OPERATION OF MAGNETO RHEOLOGICAL FLUID CLUTCH
John Janiszewski       THE EFFECT OF THE JAPAN TSUNAMI AND EARTHQUAKE ON THE AUTOMOTIVE TRANSMISSION INDUSTRY
Matthew Koppey         THEORY AND OPERATION OF CONTINUOUSLY VARIABLE TRANSMISSIONS
Donald Le Clerc         THEORY AND OPERATION OF POWERTRAITS FOR NATURAL GAS COMPRESSORS
Alan Mattice           THEORY AND OPERATION OF A CVT APPLICATION IN AN INDUSTRIAL LATHE HEADSTOCK
Zachary Miller         BICYCLE POWER TRAIN
Shaynae Moore          THEORY AND OPERATION OF THE FAIRPORT LIFT BRIDGE
Chuck Nwapa            THE IMPACT OF THE JAPANESE TSUNAMI AND EARTHQUAKE ON THE POWERTRAIN INDUSTRY
Matthew O’Neill        THEORY AND OPERATION OF A MODERN CAMARO MANUAL TRANSMISSION
Zeeshan Phansopkar     THEORY AND OPERATION OF THE TOYOTA “ECT-i” ELECTRONICALLY CONTROLLED AUTOMATIC TRANSMISSION
Robert Priotti         OPERATION OF LIMITED SLIP DIFFERENTIALS
Bradley Sawyer         OPERATION OF THE GENERAL MOTORS TURBO-HYDRAMATIC 400 AUTOMATIC TRANSMISSION
Jonathan Shannon       TOYOTA PRIUS; TOYOTA HYBRID SYSTEM
Mason Verbridge        TRANSMISSION / GEAR RATIO OPTIMIZATION
M1 ABRAMS MAIN BATTLE TANK

Andrew Baglio
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

This report will identify the technology incorporated which allows the M1 Abrams Battle Tank to be propelled by a high speed, high power turbine engine. We will identify the gearbox used to scale down turbine output and explain how this type of gearbox functions. The automatic transmission will be assessed based on its unique characteristics and its packaging for the application. The power path from the transmission will also be described, as it is routed to the tank’s tracks in a manner which allows the vehicle to be propelled forward and turned using a change in velocity between the tracks. In addition to an overall view of the system, there will be a focus on the operation of the automatic transmission.

BACKGROUND

The powertrain of the M1 Abrams is a complicated and extensive system which transfers the torque needed to propel a 67 ton vehicle. The M1 in all its forms has been powered by the same engine and transmission combination (sourced by Honeywell and Allison respectively) since it entered service in 1980. The M1 has proven to be very reliable in the extreme conditions it was built for and upgrades have kept the units in service on the cutting edge of military technology. 6,000 of the original variant, 3,000 of the M1A1, and over 600 of the M1A2 have been produced, with the M1A3 in development and slated to begin operation in 2017.

The drivetrain of the vehicle must transfer the power from a 1500 hp gas turbine to the tracks of the vehicle, which requires 3 major considerations. The first obstacle is the high output speed (over 22,000 rpm) of the engine. Second is the operating characteristic of a turbine engine, which operates best at a near constant speed and within a relatively narrow range (which is made narrower by the reduction in output speed). The third consideration is the steering of the vehicle. Unlike most vehicles that can turn wheels to change direction, tanks must provide a speed differential to the two tracks to allow them to turn.

The complexity of the drivetrain is necessitated by these considerations, the first two being uncommon even among tanks, which generally use a diesel engine. Despite its complexity the system must be durable and reliable. Any failure that disabled the tank could not only compromise the safety of the crew, but could also jeopardize the mission. With a combined weight of nearly 7,000 lbs. for the engine and transmission it is obvious that durability comes at a cost, but this is over 3,000 lbs. lighter than a similar diesel setup thanks to the high power density of the turbine engine.

DESCRIPTION OF THE TECHNOLOGY

The M1 Abrams is powered by a Honeywell AGT-1500 gas turbine with a maximum output of 1500 shp. The drivetrain of the M1 Abrams includes a large number of components due to its fairly unique setup of using a gas turbine to power rotating tracks. As power is created by the turbine, it passes from the turbine shaft through a gearbox before reaching the output shaft. At the output shaft the unit creates 2,750 lb-ft of torque at its maximum output speed of 3,000 rpm, or as much as 5,000 lb-ft at around 400 rpm.
This output torque is transmitted through a 6-speed automatic transmission (figure 2) via a hydrokinetic drive (torque converter). This transmission provides 4 forward gear ratios as well as 2 reverse gear ratios, making it unique, as most transmissions provide only a single reverse speed. Torque outputted from the automatic transmission is split between a right and left planetary gear set, which correlate with a right and left final drive output. This power split is regulated by a hydrostatic pump which varies the torque split to provide a steering input to the tank’s tracks. From the final drive output a sprocket is driven which drives the tracks.

LITERATURE REVIEW
The first true automatic transmission was the GM Hydra-Matic, which appeared in 1939. This transmission used three planetary gearsets to provide 4 forward speeds and reverse, though it lacked a torque converter and used a simpler fluid coupling. The transmission was used in 1940 model-year Oldsmobile vehicles and was offered as a $57 option in its first year. By the time passenger car production was halted for the World War II, almost 200,000 of these transmissions had been sold. During the war the Hydra-Matic was used in military vehicles, such as the M5 Stuart tank.

In 1948 Buick introduced the Dynaflow fully automatic transmission which incorporated a torque converter and was the model for the modern automatic transmission. In the early 1950’s the Chevrolet Powerglide was introduced which incorporated only 2 forward gears, but could deal with the larger torque loads required by larger cars and trucks. Transmissions like the Powerglide continued to be offered through the 60’s and early 70’s due to the large power outputs of the muscle car era, though Cadillac began to offer the 3-speed Turbo 400 in 1964.

The need for higher efficiency in the mid-to-late 1970’s resulted in the need for transmissions that incorporated more gears and provided overdrive gears (which the earlier 4-speed transmissions did not). Transmissions also began to incorporate locking torque converters, which are now used in nearly all automotive applications. In the 2000’s when efficiency one again became a priority, 5 and 6 speed transmissions, like the Allison 1000, became more common even in truck applications.

As newer transmission technologies become available, the traditional automatic continues to hold its position in high power applications due to its strength and reliability. CVT transmissions, for example, cannot support the high torque loads of truck applications. Automated manual transmissions on the other hand have shown their strength in sports car applications, but their complexity and cost are currently limiting factors.

OPERATION OF THE TECHNOLOGY
Torque leaves the turbine via a ccw rotating shaft and feeds into a planetary reduction gearbox. This gearbox provides a speed reduction and torque multiplication and retains the counterclockwise rotation of the shaft.

A splined shaft mates the engine to the torque converter, which acts as a fluid coupling to feed power into the transmission. The torque converter, which rotates ccw, feeds power to a parallel shaft via a cylindrical gear. This shaft rotates cw and has a bevel gear on the end opposite the cylindrical gear. A second bevel gear resides on a shaft perpendicular to the first. This shaft turns ccw (when viewed from the left side of the vehicle) and mates via a cylindrical gear to the main transmission shaft, which spins cw.

The planetary gearset scales the speed and torque of the shaft. In low gear, the ring gear is held stationary by clutches. Torque is inputted through the sun gear and is outputted through the planet carrier, still in the cw direction. When the sun gear is held stationary and power is inputted through the planet carrier, power leaves through the ring gear, once again cw, at a different ratio. Finally, by holding the planet carrier stationary and inputting torque to the sun gear, power is outputted in the ccw direction. Torque then passes through a second planetary gearset which provides two different output options, both maintaining the direction of rotation.

Power in transferred through two hydrostatic pumps, one at either end of the main transmission shaft. These pumps transfer power to the final drive planetary gears and allow the amount of power to be varied between the driveshafts, which allows for turning the vehicle. The input to the final drive is through the sun and the output is through the ring gear, which acts as a hub to which the drive sprocket is
attached. This final drive changes the direction of rotation, providing a final ccw rotation to the sprockets (in the four forward gears).

THEORY OF THE TECHNOLOGY

![Equations](https://latex.codecogs.com/png.image?\begin{align*}
(1) \quad GR &= -\frac{\text{Number of teeth of input gear}}{\text{Number of teeth of output gear}} \\
(2) \quad GR_A &= 1 + \frac{R}{S} \\
(3) \quad GR_B &= \frac{1}{1 + \frac{R}{S}} \\
(4) \quad GR_C &= -\frac{R}{S}
\end{align*})

The gear ratio for the cylindrical gears in the system is shown in equation (1). The negative sign in the equation show the change in direction of rotation.

The operation of the planetary gearsets follows equations (2) through (4). Equation (2) shows the ratio when the input is provided through the sun gear (S) and the output is from the planet carrier, with the ring gear (R) held stationary. Equation (3) is used when the planet carrier is used as the input, the sun is held, and the ring gear is the output. Equation (4) applies when the input is the sun gear, the planet carrier is held stationary, and the output is the ring gear. The negative sign shows the change in direction of rotation.

Due to the complexity of the system, the efficiency of the gears comes in to play. Both the spur gears and the planetary gears are very efficient, about 99% and 97% respectively. If we carry this efficiency through the system we see an efficiency of about 86%. This applies only to the gears and does not include the losses from the torque converter (about 5%), the hydrostatic pumps (as much as 25%) and the bearings. This means the total driveline efficiency can easily be as low as 60%, which can be compared to 85-90% in a passenger car.

DISCUSSION

The current technology used in the M1 will likely be around for future generations of the tank. The high load requirements of the system make it a difficult application and requires a robust design. Most vehicles of the same weight use a manual transmission because of its ease of maintenance and efficiency. In the M1 the primary requirement is ease of operation in a large variety of conditions, making the automatic transmission ideal.

CONCLUSIONS AND RECOMMENDATIONS

Because of the low efficiency and complexity of the current system, I believe a hydrostatic drive would be a good alternative to the current design. By using hydraulic motors the "gearing" of the system can be done similarly to a CVT transmission, which allows a great deal of flexibility with the system design. A reduction from the turbine would still likely be required, as most hydraulic pumps operate far below the turbine’s 20,000+ rpm output. By using two drive motors the tank’s two tracks can be driven independently, much like they are now. The system would be simplified significantly from the current design.

Hydraulic drives are commonly used in large equipment, like construction vehicles, and are fully capable of the extreme requirements of the system. With proper maintenance hydraulic systems can be extremely reliable and are easy to repair. These systems can operate in the extreme conditions required and would likely be much cheaper than the current automatic transmission.

The disadvantage of the hydraulic drive is its inefficiency. This type of system would likely have similar efficiency as the system that is currently in use. This efficiency depends greatly on the operating conditions. The system can be optimized for the most common situations (15 mph travel for example), which may allow for a higher efficiency than the current system.

REFERENCES

ABSTRACT
This paper discusses hydraulic transmissions, including hydraulic couplings, torque converters, and closed-loop pump-motor systems. Each type of hydraulic transmissions is discussed in detail, including component breakdown, how each type works both in theory and how it operates, some history of where the technology originally came from and how it’s progressed, and what the future holds for each type of transmission.

BACKGROUND
Hydraulic transmissions include hydraulic couplings, torque converters, and closed-loop pump-motor systems. Hydraulic couplings, or fluid couplings, and fluid couplings, are hydrostatic devices and encompass torque converters.

Fluid couplings are being used in the automotive industry as an alternative to the mechanical clutch as well as in marine and industrial applications. The principle of pressure transmission using a hydraulic fluid was first stated in 1653 by Blaise Pascal. Joseph Bramah’s hydraulic press of 1795 implemented Pascal’s principle of constant pressure in a closed system. World Wars I and II saw the widening of hydraulic transmission application. The hydrodynamic torque converter replaced simple fluid couplings in engines in the 1940s. Today, almost all automatic transmissions use torque converters to switch between gears instead of the mechanical clutches used in manual transmissions. The concept of using hydraulic fluid as a means of transmitting force has been around for over three and a half centuries, but the technology is still advancing with new developments in the automotive industry.

For steam engines, unlike internal combustion engines, the engine can be stopped and started when the operator wants to apply or remove torque from the load. The engine operates well at low speeds and can handle heavy loading at these speeds. For internal combustion engines, it is necessary that the engine be allowed to run without any application of torque to the load and they must be able to run at high engine speeds while starting their loads. A clutch allows for a short period of transition between full disengagement and full engagement, so as not to shock the system. Torque converters are an alternative to clutches, used especially for automatic transmissions. They allow the engine to spin independently of the engine.

Closed-loop pump-motor systems are another type of hydraulic transmission. Some common applications are the swing drive for rotating the boom on excavators and cranes, ships’ rudder controls, fin actuators for ship stabilization, and farming and industrial equipment.

DESCRIPTION OF THE TECHNOLOGY
Hydraulic couplings consist of an impeller, turbine, and housing, as can be seen in Figure 17. The impeller is attached to the housing and the input shaft. The turbine is attached to the output shaft. The impeller and turbine are facing each other and are surrounded, inside the housing, by fluid. The fluid is generally a light oil that either completely or mostly fills the cavity.

Torque converters have the same housing, impeller, and turbine setup as generic hydraulic couplings, but they also have a stator in the middle. The components can be seen in Figure 49, the impeller, or pump, (on the left) connects to the flywheel (and thus, the engine) and the turbine (right) is fixed to the transmission, or load.
The shaft from the engine enters on the right. It attaches to a swashplate. Spring-loaded pistons move with the swashplate. Often closed loop systems require an additional smaller pump to help with pressure losses, discussed further later in the paper.

**LITERATURE REVIEW**

Pascal’s Law, first stated in 1653 by Blaise Pascal, professed that the pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions throughout the fluid, shown with simple values in Figure 34.

Joseph Bramah introduced the hydraulic press in 1795. The use of a simple hydraulic pump being used repeatedly to lift a large weight is shown in Figure 112. This represents the first notion of using hydraulic fluid as a form or transmitting force or energy.

In 1840, Lord William Armstrong of England published in ‘Mechanics Magazine’ an article concerning energy gained from lifting a fluid up a certain height. He claimed that when water is lifted by a pumping device, it receives the energy used in raising it. In its descent, it becomes a medium through which the energy of the pumping device can be transmitted at a distance.

In 1923, George Constantinesco invented the first concept of the torque converter, as shown in Figure 55.
Figure 55: Constantinesco’s torque converter.

Daimler introduced the fluid flywheel in 1930, an innovation in hydraulic couplings on automobiles. It was combined with a pre-select gearbox to provide “unrivalled smoothness” compared to a manual transmission.

In 1918, Twin Disc designed a clutch to make farm tractors more reliable. Today, they’ve grown into the development and manufacture of both off- and on-road vehicles including Aircraft Rescue Fire Fighting (ARFF), oil rigging servicing vehicles for Siberia, tunnel cleaning machines for subways, and farm equipment, all using automatic hydraulic transmissions. A microprocessor senses when to shift without any loss of power, knows when to deliver maximum acceleration and traction in all conditions, and knows when to disengage the differential lock to prevent over-stressing the axles.

OPERATION OF THE TECHNOLOGY

For hydraulic couplings, the impeller, attached to the input shaft, rotates at the same speed as the input. The fluid inside the housing gets sucked through the impeller as it rotates and is pushed through the turbine, causing rotational motion. Since the turbine is connected to the output shaft, the motion is transferred through the hydraulic coupling. The turbine is able to be held still so no motion is transferred even if the impeller continues to rotate.

In torque converters, the impeller, or pump, input shaft rotates with the engine, as can be seen in gray in Figure 26. The fluid within the housing moves through the vanes of the impeller as it rotates, then causes rotational motion of the turbine, shown in green. This causes the rotation of the output shaft, generally to the transmission.

The stator, seen between the turbine and pump in Figure 26, generally remains stationary during low pump/turbine rotational speeds, then, if a one-way clutch stator is installed, is ‘allowed’ to spin with the turbine at higher speeds. The transition usually occurs around 40 mph.

Closed-loop pump-motor systems have a fixed- or variable-displacement pump attached to the input shaft from the engine. This pump transfers the rotational motion of the engine into fluid flow, which runs through lines to wherever it is needed, e.g. motors at the wheels. The hydraulic fluid can be seen in red in Figure 93. The motor, which is powered by the hydraulic fluid, outputs rotational motion. Once the energy in the fluid has been harnessed, it travels directly back to the pump in a closed loop, seen in green.

A smaller additional pump also runs to compensate for the pressure losses due to leaks in the pump, etc. Some systems have a supercharge pump relief valve which allow for flow through the piston pump housing to remove excess heat when pumps are idling. Similarly crossport relief valves are often added to prevent excessive loop pressure if there are high inertia loads on the motor and pump flow is suddenly reduced.

The axial piston pump uses a rotating swashplate and spring-loaded pistons to move the fluid. As can be seen in Figure 2, as the swashplate, attached to the input shaft, rotates, the spring-loaded pistons move up and down. This motion sucks fluid in (shown in green) and pushes it out (shown in red) at either a constant or a variable rate. For a fixed-displacement pump, the swashplate is always at the same angle. For variable-displacement, the swashplate can swivel back and forth to allow the pistons to travel further or shorter distances to increase or reduce the flow. Swiveling the swashplate can also quickly reverse the flow. As can be seen in Figure 44, the valve plate on the left shows the inlet and outlet sections where the fluid is pumped into and out of.
As the load increases, pressure increases, and the pump and volumetric efficiencies decrease as the motor begins to slow down. This causes the voltage in a tachometer generator, which produces a voltage proportional to the motor speed, to drop. This drop causes a servo amplifier to produce a current which makes the torque motor armature, and subsequently the swashplate, to rotate. This increases the pump displacement such that more fluid flow is delivered to the motor and speed can increase.

THEORY OF THE TECHNOLOGY

The premise of both hydraulic couplings and torque converters is fluid motion transfer. As the impeller spins each drop of fluid at the inner edge of the impeller vanes is moved through centrifugal force to the outer edges of the vanes. The vanes can be straight or at an angle to the impeller radius, as seen in Figure 91.

Each drop of fluid exiting the impeller has a rotational speed component in a plane perpendicular to the radial plane that is equal to the speed of the impeller. These drops exert a force on the vanes of the turbine which causes it to spin in the same direction as the input shaft.

For the torque converter, the stator acts as a guide to transfer the fluid from the exit of the turbine to the inlet of the impeller more efficiently. One-way clutches are often used to allow the stator to spin in one direction. The stator’s purpose is to change the direction of the flow to prepare the fluid to enter the impeller. Around 40 mph, the impeller and turbine are moving at around the same speed, so the fluid exiting the turbine is already moving in the same direction as is needed for the impeller. Thus the stator is no longer required. The fluid starts hitting the back of the stator’s blades and causes the stator to rotate (through use of the one-way clutch) so as not to inhibit the fluid flow. The one-way clutch, as seen in Figure 52, uses friction between the outer ring and the rollers to prevent movement. When the ring tries to move clockwise, the rollers get wedged between the hub and the ring and prevent the ring for spinning. When the ring tries to move counter-clockwise, the rollers push the springs in and allow the ring to spin.

The closed-loop pump-motor system uses fluid flow as a means of transferring energy. The pump converts the rotational motion created by the engine into hydraulic flow, which is transferred through lines to motors. These motors transfer the energy back into rotational or other forms of energy to perform whatever task is required. The axial pump uses Pascal’s law: pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions throughout the fluid. Thus the fluid brought into the pump must exit the pump at the same pressure, subsequently moving the fluid through the hydraulic lines.

DISCUSSION

In 1949, the first lockup clutch for a torque converter was introduced on Packard’s Ultramatic transmission. The clutch locked up the input shaft to output shaft so there would be no losses due to the fluid. The concept did not stick because of the extra cost and complexity of the technology. For increased fuel economy purposes, the concept was reintroduced in the 1970s and is present on most automotive torque converters today.

Companies like Twin Disc are continuing to move hydraulic transmission technology forward. They are designing unique and creative solutions to difficult scenarios using hydraulics transmissions. Hydraulic transmissions are being used considerably in construction and farm equipment today and should become more prevalent as time goes on.

CONCLUSIONS AND RECOMMENDATIONS

Torque converters can give two to three times more torque to the car when accelerating from a stop. However, automatic transmissions often have lower efficiencies than manuals, partly because the pump is always moving a bit faster than the turbine. To reduce this discrepancy, some torque converters use the lockup clutch so the input shaft is directly connected to the output shaft, thus no loss in efficiency. This technology should remain present in torque converters in coming years.

Since closed-loop pump-motor systems can have variable pumps and/or motors, they can easily be made into continuously variable transmissions. Thus there
are no gears; the operator can just keep applying more power until it is maxed out. One- or two-speed displacement pumps provide a constant, instead of infinitely variable, amount of torque. While these have their limitations, they are cheaper and more reasonable for construction or farm equipment which might need one speed and torque rating for working and another for short-distance road travel. The efficiency of these types of transmissions is generally around 80%, compared to the 95% of traditional discrete-gear transmissions. However, there are many benefits which often make up for this fact. As stated before, there are an infinite number of torque/speed settings and no interruption of power. Thus full torque is available at any speed. It also adds less inertia to the total rotating mass of the engine than traditional transmissions, so it can change speed more quickly. Switching from forward to reverse is accomplished simply by moving the swashplate. While there is generally only one pump, there can be hydraulic line connecting this pump to separate motors at each wheel, so slip at one wheel wouldn’t affect the other wheels. Another benefit is that the pump speed is generally unaffected by load variations. The entire system is also a much lower cost than a system comprised of a gearbox, driveshaft, differential, clutch or torque converter, etc. Since the traditional transmission has been used for so many years, closed-loop pump-motor systems have yet to reach their full potential in automobiles. However, in coming years, the technology for this type of transmission should improve greatly and they may start being seen on vehicles.

REFERENCES

CNC VERTICAL MILL

Jeffrey Bird
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
Nothing is more impressive than watching a machine take a simple square piece of metal and turning it into a wildly complex part. Vertical CNC mills are capable of exactly that. Computers allow for complex motion control and behind the scenes calculations to take place on the spot, but none of its capabilities would be possible without a solid drive train to convert all of the computer commands into smooth accurate and powerful motion. Design of such a system is more intense than just picking an actuator and assembling the machine. Quite a few factors play into the size and power requirements of the linear actuators as well as the spindle drive. Many components have features unique to the application of CNC machinery. The factors and features are described in-depth as well as the reasoning for each.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Velocity</td>
<td>(in/s)</td>
</tr>
<tr>
<td>a</td>
<td>Acceleration</td>
<td>(in/s²)</td>
</tr>
<tr>
<td>J</td>
<td>Inertial</td>
<td>(in – lb – s²)</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
<td>(in – lb)</td>
</tr>
<tr>
<td>w</td>
<td>Rotational Speed</td>
<td>(rpm)</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
<td>(lbs)</td>
</tr>
<tr>
<td>W</td>
<td>Weight</td>
<td>(lbs)</td>
</tr>
</tbody>
</table>

Subscripts & Superscripts
Table With respect to the machine table
Motor With respect to the servo motor
Friction Quantity dictated by friction
Actuator Value dictated by the actuator system
Load Property of the table load

BACKGROUND
CNC vertical mills are the workhorse of the manufacturing industry. Capable of running parts 24 hours a day and 7 days a week, these machines will run tirelessly to produce parts. The ability of CNC machines have greatly improved quality of manufactured goods as well as the speed at which they can be produced. From an economic standpoint, more products sold for the company and better quality products for the consumer. From an engineering standpoint, CNC vertical milling machines allow new, higher strength materials to be cut accurately making otherwise impossible designs now possible. The benefits of CNC technology clearly out weight the cost associated with the machines and perishables. Complex geometry that couldn’t possibly be machined by hand can easily be interpreted and performed by the computer and motion control system. The basic CNC mill system is well defined, but areas for improvement are still being sought after. High speed machining is an example of this. The high speed machining process pushes milling machines ever faster. Through better analysis of the vibration characteristics in materials speeds could be increased even more. Innovations have also brought about huge advancements in dry machining. Dry machining saves companies in coolant and disposal costs, and improved work environment. The development of new tool coatings have aided in the move to dry machining. According to the census data, employment in machinery manufacturing is increasing. This provides the perfect opportunity for innovation in the machine tool industry. With an increased demand for machine tools, the next big break thought could play a key role in turning around the US economy. [1]

DESCRIPTION OF THE TECHNOLOGY
A CNC Vertical Mill is really a combination of somewhat simpler systems which can be seen in Figure 1.

![Figure 1. Flow chart illustrating basic CNC machine control hierarchy. [2]](image-url)

The basic vertical mill which is very closely related to the manual version simply bulked up to handle greater forces, three linear actuators with the added possibility of rotary actuators as well, to control machine motion, and finally the computer system to aid in movement tracking as well as on the fly calculations. The vertical mill is represented in figure 1 by the “table” block referring to the machines work table. The servo motors are clearly represented and the “count comparator” and “feedback device” refer to the electrical motor controls. The first two blocks in figure 1 represent the machines computer and input in the case of CNC.
would be a program generated in machine language. The complexity of this system comes from how all these parts work together to achieve and maintain motion in a very precise manner. The linear actuation is generated through ball screw slides attached to AC servo motors. The servos are controlled through an electrical control box that outputs the proper amount of power for each move required. The computer used in the milling machine is what would be considered the “brain” to read the program and essentially operate the electrical controls creating the desired motions. The computer also controls the spindle speed including accounting for changes brought on by cutting force. Figure 2 shows the travel created by the linear actuators of a vertical mill.

![Figure 2. Principal motion of a vertical mill. [3]](image)

The X, Y, and Z axes are considered the principal degrees of freedom for a vertical milling machine. The A and B axes can be added with two rotary actuators. This can either come in the form of what is know as a forth and fifth axis table or integrated into the motion of the spindle itself. Figure 3 demonstrates the additional two axes on a table.

![Figure 3. Motion of axis for vertical milling center. [4]](image)

The axes are the degrees of freedom of the machine and what all the components work together to control with speed and accuracy. With 5 axes of motion, the shapes the machine can create are only limited by how the piece of stock is held.

**LITERATURE REVIEW**

The vertical milling machine was developed long ago. In 1818 Eli Whitney created the first milling machine. This machine had hand cranks to move the work in the x, y, and z direction similar to the knee mill of today. While the vertical mill itself does not stem from a recently developed technology, the CNC portion is a relatively recent innovation. The first variation was called NC or numerically controlled. This allowed a simple mill with servo motors attached to read punch cards. The NC system was developed in 1952 by John Parsons. The machine was able to perform complex operations such as curves via the attached computer reading punch cards. This was a huge improvement at the time because of the near impossible task of creating an accurate arc with hand operated controls. The next improvements came with the advancement as well as size reduction of computers. More advanced computers allowed programs to transfer to tape reels and eventually be stored solely on the computer itself. The systems of today have come a long way in a short time. The advanced machines today read programs stored directly on the computer that can be generated from 3D models using CAD/CAM programs. CAD/CAM enables the user to easily optimize tool paths and cut parameters. The software is capable of not only reducing manufacturing time, but also improving surface finish quality. Advancements in programs allow for extremely complex geometry to be machined. Current development in the field of CNC come more from larger companies such as Haas, Milltronics, Toyoda, Fadal, and Okuma. The focus of development in CNC has shifted to high speed machining, which possess a whole new set of issues concerning vibration frequencies and how they affect the metal cutting process as seen in figure 4.
The spikes of stable section demonstrate how narrow the window is for finding a stable cutting speed and feed rate when the spindle rpm begin to climb. Careful analysis must be performed to match these parameters to protect the machine and part from serious damage. The tradeoff is new machines are pushing the material removal rates beyond any that have come before.

OPERATION OF THE TECHNOLOGY

The axis drives of a CNC mill operate via ball screws. Ball screws are very well suited for this application; they have a high degree of precision in linear motion that lends itself perfectly to the task of machining a part. This type of mechanism also allows for very smooth motion. Smooth motion is key for interpolating cuts with a great degree of precision. Ball screws also have the capability to execute extremely fast moves. Fast motion becomes important in both fast feed cuts as well as rapid moves. Any time spent moving the cutter around without taking material off is wasted time in an operation. Minimizing that time is a key component in lean manufacturing processes. The ball screw turns rotational motion to linear motion through a collar with ball bearings riding in the spiral track of the screw. This mechanism is part of what gives them their smooth motion. One key issue with such a setup is keeping the system well lubricated and dirt free. An oil system is used to reduce friction and keep motion smooth. Keeping dirt out of internal components is also essential, and accomplished through wipers that rise along the screw to catch any dirt before the collar moves over the surface. Dust guards are also commonly used to keep chips out and prevent damage from any sizable scrap that may come off a part. The ball screws can be driven both clockwise and counter clockwise depending on the direction of motion required. Figure 5 shows an assortment of ball screw linear actuators similar to what would be used for table control on a CNC mill.

The actuators in Figure 5 are all directly driven by AC servo motors, however it is also possible to use a belt or gear drive system on the end of the ball screw. This is commonly seen on the z axis actuator because of the increased load. The direct drive method does allow for the most accuracy by eliminating any components that could induce backlash in the drive system. The z axis will have another added feature used to avoid possible issues in the event of power failure to the z axis servo. This is a mechanical brake that is applied to the system if power is lost to the servo, preventing the head of the machine from crashing down to the table.

Rotary actuators will be controlled through a servo motor running a fairly high reduction gear system to give them both a high degree of precision and high speeds needed to execute radial cuts. Servo motors are the best choice for the CNC application because of the high controllability, and when combined with a feedback loop, the ability to measure the actual traveled distance versus desired distance. All of these components come together under the control of the computer to accurately move the workpiece around to make cuts. Consideration must also be given to the dive of the tool itself.
The spindle drive is responsible for enduring huge loads while keeping the tool spinning at high rpm. Figure 6 shows a spindle drive system capable of 180,000 rpm.

![Figure 6. Spindle drive system [8]](image)

Special attention is given to bearing location in an application such as this. With large cutting loads being subjected in all directions it is necessary to have sizable bearings as close to the tool holder as possible. This is shown in figure 6 by the set of two bearings mounted just inside the tool side of the spindle. The high rpm demands of machine tools also play a role in the need of high quality bearings and a well lubricated system. One system developed to further protect the bearings is called an air purge spindle. This system maintains a stream of compressed air flowing through the bearings to keep dust, coolant, and other contaminants out of the bearing system. [8]

The drive for a vertical mill spindle is commonly a direct drive DC motor. DC motors are a good candidate for vertical milling application because of their wide rpm range and high torque capacity. Milling machines can demand speeds anywhere from 2 to in excess of 30,000 rpm. DC motors have the versatility to accomplish this as expected from a CNC machine. Belt drives are also incorporated at times for lower speed higher torque machines. [9]

THEORY OF THE TECHNOLOGY

The theory being the motion of a CNC system is fairly simple. Equation 1 below demonstrates how to calculate the velocity of the table based on the motor speed and lead of the ball screw.

\[ V_{table} = \frac{w_{screw} \times \text{Lead}}{60 \times 25.4} \]

The equation emphasizes the key components in determining the behavior of the drive system. What is happening on the motor side, and the lead of the ball screw applied. These two factors play a large role in determining the characteristics of table motion.

Equation number 2 shows the calculations to determine force applied on the table based on motor torque and friction of the system. This is an important parameter to calculate because if the table cannot overcome the cutting forces generated by the machine, the table may not move as expected. If the table is not moving as directed by the control, the machine will fault and shut down the machine.

\[ F_{table} = \left[ T_{motor} - T_{friction} \right] \frac{25.4}{2 \pi \times \text{Lead}} \]

Again in equation 2 the effects of screw lead and motor torque can be clearly seen. Friction must also be taken into account as the force actually applied will be decreased through the friction of the system. A calculation for force is also important for the z axis. The z axis drive component will have the weight of the entire spindle drive riding on the dive system. If the torque of the servo motor is calculated incorrectly or doesn’t take the friction into account, the z axis may not move due to a friction lock or even worse crash down to the table due to a lack of power.

Equation 3 is used to calculate the maximum possible acceleration of the dive system. It is important that the acceleration is quick at speeds used during cutting because any distortion in the movement translates into poor tolerance control in the process.

\[ a_{table} = \frac{a_{motor} \times \text{Lead}}{2 \pi \times 25.4} \]

Equation 3 depends on motor acceleration and lead of the ball screw as well. The lead and motor characteristics affect all aspects of the drive system.

Equation 4 brings into focus one of the most important aspects of the table drive system, and that is the inertia. For the control of the part to be smooth and accurate the inertia of the actuator and load inertia must be matched to give an advantage to the actuator. This means that the maximum table load will be determined by the ability of the motion system to handle inertia as opposed to strictly how much weight can it support.

\[ J_{load} = \frac{W_{load} \times \text{Lead}}{g \left( \frac{2 \pi \times 25.4 \times \text{ratio}}{2 \pi \times 25.4} \right)} \]

In the equation there is a term to account for any drive system ratio that may be incorporated like a belt system to increase the actuators advantage.

Equation 5 is the ratio of load inertia to actuator inertia. This ratio should be at a maximum of 1. This means giving the advantage to the actuator making the motion of the part easier to control with accuracy. This also means that ignoring the max suggested load just because the table can support the part, doesn’t guarantee parts within tolerance.
Inertial Ratio = \frac{J_{\text{Load}}}{J_{\text{Actuator}}}

When the inertial ratio is greater than one a phenomena known as table coasting occurs. This is when the control tells the servo motors to stop and the table briefly continues to move due to the momentum of the part. The amount of momentum in the table is directly related to the amount of inertial contained in the load; therefore any problems with coasting can be avoided by properly sizing the actuators for the type of work being done. [10]

DISCUSSION

The future of CNC technology is heading into high speed machining where vibratory signatures become extremely important. As the technology for monitoring these vibrations advances machines will be able to push the cutting speeds faster and faster. Another area of improvement is tool materials and coatings. The tool strength affects the rigidity of the overall machine when preforming an operation. Also more advanced materials could extend tool life enabling many more parts to be made per perishable tool. Coatings are improving the abilities of dry machining, eliminating the need for coolants. While some operations still require coolant for high volume chip removal and in some cases reducing built up heat, more advanced tools are ever closer to solving such issues.

CONCLUSIONS AND RECOMMENDATIONS

CNC mill technology has come a long way from the first punch card reading machines of 1952. However, there is still room for improvement. The next step will come from more advanced materials allowing machines to push even faster in the cutting process, also with more powerful software increasing the ease of use and better planning of all the cutting operations required by a single part. Through these improvements, the time saved in manufacturing of parts would increase as well as number of pieces that could be produced in a single work day. Improvements in the controls could come from reduced cost of components of the actuators as well as reducing overall machine size. Further automation such as tool breakage sensors automatic blank loading could also increase productivity of the machines, allowing long production runs to be made unsupervised. The move to dry machining will help to improve the environment, by eliminating the need more oil and water emulsions. Coolant free chips can also be more readily recycled to make new pieces of metal.

REFERENCES

DRIVETRAIN THEORY AND OPERATION FOR USE IN BAJA SAE COMPETITIONS

Charles M. Borton
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
The purpose of the Baja SAE series is to test students against one another in critical real life situations of engineering design and management. One of the most influential pieces of this process is the build and design of the vehicle. A vehicle cannot run without a power train. The Powertrain for an off road Baja car is an extremely pivotal part of the design process and the cars build as a whole. Without a power train there is no way to transmit the power generated from the engine to the wheels. This paper is focused on the theory and operation of the drive train for the Baja SAE application. Some teams will build a car around the power train that is store bought, be it for an ATV, a snowmobile or some other similar applications. Other teams, like the one I'll focus on, design the entire car for optimal performance and design the subsystems within that. This way, it allows the designers to be constrained to a given space, but still have to produce maximum performance. The overall goal is to outline the design and function of a not so typical power train for the Baja SAE application and discuss its pros and cons as well as outline the design parameters and discuss the challenges and pitfalls of the system. The power train in its most generic terms encapsulates the entire system from the output of the motor to the wheels on the ground. While III touch on the entire system my main focus will be on the reduction gearbox mostly, as it is the most integral and most heavily designed features of the system. In the grand scheme the rotation of the output shaft of the motor provides the original torque and rotational motion that will eventually get to the wheels to move the vehicle. My goal as a whole is merely informative to introduce the reader to this complex system and to detail its importance and also justify its use over much simpler, yet more inefficient systems.

NOMENCLATURE
Definitions of terms used.
Continuously Variable Transmission: The CVT is a type of transmission system that has a belt or chain running in tension between two parallel bevel wheels of variable diameter. It provides a wide range of effective ratios and varies based on the input torque/rotation provided by the motor. It can also impede the motor with backpressure.
Input Shaft: The input shaft is a shaft that is connected both to a power source and to a device it is transmitting power to. The input shaft is spun by its power source and spins with it to power the device its attached to.
Output shaft: The output shaft is the final shaft spun before the power is transmitted to the wheels. Splined shafts are connected both to the wheels and to the output shaft to provide the final link.
Ramsey Silent Chain: A chain with inverted teeth. “Silent chains are made up of stacked rows of flat, tooth shaped driving links that mesh with sprockets having compatible tooth spaces”[1]
Ramsey Gear: A gear with a much wider facewidth than typical sprockets, made specifically to mesh to the Ramsey Silent Chain.

BACKGROUND
The structure of the Drive train for a Baja application is extremely complex and varies as much if not more than any other system within a vehicle. The Baja driveline doesn’t just compose of one form of power train systems but is a combination of many. This is why it is so important. Although seemingly complex the arrangements of gears chains and shafts seem to come together flawlessly in a magnificent system that somehow implements a multitude of translating and rotating parts of varying masses, but still manages to be efficient. This small scale performance technology is vital to the advancements of large scale technologies in the future.

Because this technology varies so much within the Baja SAE series, I’m going to focus on the newest development here at RIT running our first ever differential within our transmission. I’m choosing to focus on this particular power train because of its design features and the effect it has on the dynamical capabilities of the Baja car beyond just power transmission. Fewer than 10 percent of teams at any given Baja SAE event will run a differential, and even fewer will run one successfully.

The main purpose of the Power train system within a Baja car is to transmit all the rotational energy of the engine, to the tires planted on the ground. To do
so a delicate balance is required. Any given team has to decide between high torque and quick acceleration or a slower acceleration with a higher top end speed. This is a mature technology that doesn’t change much from a design perspective but from an optimization standpoint.

The simplest power train with no calculations and a 1:1 gear ratio would be a “Live axle” with a chain drive without any reduction in-between. This would essentially have a sprocket or fixed to the output shaft of the motor and a chain that connected that sprocket to another sprocket affixed to a solid shaft that is attached to both wheels. As this occurs, all of the rotation provided by the motor goes straight to the wheels. It is an extremely simple system, with a minimal amount of moving parts and a minimal stack up of inefficiencies. The only losses in this system are attributed to the chain riding on the gears, providing that the gears are attached solidly to the shafts via welding or with mechanical fasteners. This application however, is very low tech and low performance so is not applicable to the Baja race application.

The power train I will focus on is much more complex and much more real world. The output of the motor is attached to a primary (drive) clutch. This clutch runs a secondary (driven) clutch in order to provide a torque input to the reduction box. This series of a driven and drive clutches is an example of a continuously variable transmission (CVT’s). The CVT’s are revolutionary and extremely complex on their own. The CVT relies on the centripetal motion and forces of the rotating masses to overcome and counter a series of roller weights and spring forces in order to “shift” the area of engagement on the drive belt. This belt then rides between the 2 rotating clutches in different locations along the sheaves in order to provide either better torque for traction or acceleration of less torque with a higher RPM for top speed applications. The CVT’s are a mature technology and have been in use for as long as the mainstream commercial motor sports market has been around, because of its prevalence in ATV and Snowmobile applications.

DESCRIPTION OF THE TECHNOLOGY

One of the main pieces within the Baja Driveline is the CVT Setup. The CVT is the first series of reduction/gearing off of the motor. The Drive clutch is attached to the output shaft of the motor via a keyed shaft. The Drive Clutch is attached to the driven clutch via a V belt. The driven clutch is attached to the input shaft of the reduction box by meshing the internal splines of the driven clutch with the external splines of the input shaft. Consider figure 1 which has the reduction box to show the path of power transmission from input shaft to the output shafts.

![Figure 1: Parts List:](image)

- Bearings and Seals: Located inboard and outboard of all 3 locations where the shafts enter/exit the reduction box.
- Case Halves: 10, 11, 12
- Input Shaft: 1
- Output Shaft sleeved with iolite bushing: 6
- Planets: 7(x4)
- Planet Carrier: 9
- Ramsey Gear: 2, 4
- Ramsey Silent Chain: 3
- Ring Gear: 8
- Sun Gear: 5

The Input shaft spins the attached Ramsey gear. The gear and shaft are joined via splines as well. The Ramsey gear has a ½ inch silent chain riding on it. The silent chain is attached to another Ramsey sprocket that is bolted to the sun gear and that assembly rides on an iolite bushing over the output shaft. The sun gear is meshed with the 4 planets that are held in place by the planet carrier. The planets are meshed inside the carrier to the sun gear and outside the carrier to the ring gear. The ring gear is stationary and is bolted to the case halve. The planet carrier is splined to the output shafts which are splined internally for the CV shafts to mesh with. The CV shafts extend outside of the reduction box and go to the wheels.

The overall system is in any given condition between 95-98% efficient, assuming some belt slippage of the CVT. All of the gears in this box are spur gears with an efficiency range of 98-99% so very little is lost through the reduction itself, and all that is lost is lost to the heat in the lubricating fluid. The overall efficiency is determined with a rough estimate. Ideally one would need to measure the exact output torque and speed at the motor and cross that with the inputs/outputs throughout the system to not only quantify the overall losses but to locate the biggest culprit. The rough estimate comes from the estimated engine RPM under minimal load and the RPM of the wheels back calculated from the average speed (in mph) using appropriate tire size calculating the rpm of
the wheels. Knowing that the overall reduction of the box is 7.25 you would have to induce a constant state into the CVT (having it run fully engaged or fully disengaged) to keep that reduction constant. It’s near impossible to derive the actual equations theoretically because there are so many variables and so much constant change. If I had the proper hall effect sensors and data acquisition technology I could acquire the real data and quantify the equations that way. Otherwise we are restricted to the efficiencies of the spur gears and adding a little bit of assumed losses for the slippage of the clutch belts, another value that cannot be easily quantified.

LITERATURE REVIEW

The first known CVT was sketched by Leonardo DaVinci in 1490 but it wasn’t implemented until Dutch auto manufacturer DAF first used a CVT in their cars in the 1950s. The technology at this time however was so limited that it was limited to engines with less than 100hp. Later in the 80’s and 90’s some foreign automakers started using the CVT in their mini cars. Now into the 2000’s most major manufactures have one or more vehicles with a CVT.

The original Gear reduction dates back to ancient china. No accurate date can be found for when the first gear set was ever used, but the idea has been around for as long as man has been around to innovate. There is limited literature for my specific application because the typical Baja applications are either designed 100% by the students, or bought as a stock unit that is proprietary information to the manufacturer.

THEORY AND OPERATION OF THE TECHNOLOGY

The motor rotates at 3600 RPM. Attached to the motor is the drive clutch. The drive clutch spins at the same rate as the motor as it is attached on the output shaft of the motor via a key with no gearing involved. The drive clutch drives a driven clutch via a V belt. When tuned properly, the side forces from the CVT’s on the belt will cause it to be very close to 100% efficient with no slippage. This driven clutch is attached via splines to the input shaft of the reduction box. The input shaft has a Ramsey gear (drive) attached to it. On this gear rides a silent chain. The chain runs down to a driven gear, the drive gear has 17 teeth and the driven gear 37 teeth. The sizes of these gears and the number of teeth and the gear design are all optimized and placed into a selection matrix. Overall the silent chain produces a ration of 2.176 from input shaft to the driven gear at the end of the chain. From the chain the driven gear is bolted to the sun gear. This shafted assembly all rotates on an oilite bushing so that it rotates freely and allows the output shaft to rotate inside of it. The sun gear rotates at its new speed brought forth from the silent chain reduction (in this case assuming 0 losses and the ratio of 2.176) It spins at 7,833.6 RPM. The sun gear rotates and is meshed with 4 planets that work in the planetary gear set. In this set the 4 planets rotate off of the input of the sun gear. They rotate inside of a fixed ring gear. The ring gear is bolted to the case halve and only provides a surface for the planets to push off of. The planets rotating inside of the ring gear causes the rotation of the planet carrier which is splined to the output shaft. The output shaft is splined internally to allow for externally splined shafts to be seated inside the reduction box at the output shafts, so that those shafts can turn the wheels. The main source of reduction comes from the design and arrangement of the planetary set. This depends on the size and number of planets, as well as the sizes of the ring and sun gears. The design selection matrix is a massive calculator built into an excel workbook that takes countless hours to generate. Ultimately, with the removable 3rd piece of the reduction box, the planetary set can be changed without removing the transmission from the vehicle and allows for changes in ratio instantly. The available ratios with the given set up are:

<table>
<thead>
<tr>
<th>Final Ratio</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio Low</td>
<td>7.255</td>
</tr>
<tr>
<td>Ratio Mid</td>
<td>7.545</td>
</tr>
<tr>
<td>Ratio Mid/High</td>
<td>8.125</td>
</tr>
<tr>
<td>Ratio High</td>
<td>8.706</td>
</tr>
<tr>
<td>Ratio High/high</td>
<td>9.286</td>
</tr>
</tbody>
</table>

This however is not the overall power train reduction because there is also a reduction that occurs in the CVT. This is what prevents me from giving a definitive answer on the overall geared reduction of the power train because it’s effectively continuously changing. The CVT’s will change ratios smoothly as they are intended to operate for any number of reasons. Slight changes in ambient air temperature, operating temperature and most importantly track conditions and throttle response the CVT will vary between a .83 reduction and a 2.3 reduction. Those values have the abilities to wildly vary the overall reduction ratio of the car. The reduction ratio of the gearbox however was set and selected for normal operating conditions at 7.545.

DISCUSSION

Since this is unique application of a mature technology there are no real resources or information available to review or provide insight into this application. Each team writes a design report about their given system, but all information is proprietary for the application. I see the technology as being completely wide open. Because there are no restrictions on the power train other than safety features it’s a completely open ended design question. Teams must balance performance with manufacturability and cost. For example, this year the RIT Baja SAE team added a torque sensing (torsen) Isotorque differential on top of the standard reduction box. This greatly increased the complexity of the
system but allowed for a tighter turning radius and also allowed for many other design improvements. By adding the differential the rear track width of the car was able to be wider with increased overall stability, lowered the Center of Gravity and reduced the instant roll center of the vehicle. The only loss that comes with the differential is a 10 lb increase in rotating mass and a loss of the ability to change between a wide range of gear ratios. One of the biggest advantages of the reduction box I wrote the investigation about was the ability to change ratios in the vehicle by just removing the 3rd case half and swapping the planetary set. One thing I’ve seen the most after looking at hundreds of cards with virtually hundreds of different power trains is that there is a very distinct balance between complexity and performance. If it’s so complex that you can’t tune it or make it run, then it doesn’t do you any good. But if it’s so simple that you lack adjustability and tune ability then you will probably be lacking as well. My thoughts are that this technology will continue to grow and adapt as the racing scene and students evolve. Each year we push the envelope, so each year things get a little more interesting. I’ve talked a lot about tune ability recently and there’s good reason. Consider the Figures in the Appendices. Figure 2 is a torque/hp curve of our motor generated by a team built engine dynamometer. This tells us effectively our true range of torque/power to tune to. After that, there are the ratio selection matrices in figure 3. These matrices go through all of the possible ratios and their sizes and designs in a complex team built calculator to determine speeds, both linear and rotational as well as the stresses the ratios put into the parts. In figure 3 there are some diagrams showing the ideal torque curves for proper shifting of the CVT. Tuning the CVT to the engine and the reduction box is perhaps the most critical and difficult operation because there is just so much going on in the system at one time and so many variables. It’s one of those times where simpler really is better.

As far as CVT’s go. Almost all major car manufactures have dabbled in the technology but few have made a considerable impact. Audi has made pretty large gains in the market in the past few years and have done a lot of testing and advertising, but aside from a few expensive performance models, there isn’t much out there in terms of passenger vehicles with CVT’s

CONCLUSIONS AND RECOMMENDATIONS

Going back to the CVT’s I think one of the biggest factors hindering the take off of CVT in the modern day automotive industry is the difference in the feel. A car with a CVT wouldn’t shift like a normal vehicle. You would never change gears like in a manual transmission nor feel the transmission jump when it does it automatically. Also, because the CVT is based off the motors rotation, the motor speed and sounds are completely different than the traditional automobile. The CVT can match to stay in its ideal torque range, which differs for each vehicle and situation, so it doesn’t sound like a typical car. It won’t start in a low gear being bogged down producing a lot of torque and eventually winding out to a lower RPM. I think this difference heard and felt by the driver are the biggest discouragement to the technology currently.

As far as the Baja Driveline goes, I’ve seen all sorts of setups win competitions. The biggest problems are tuning, designing and packaging. At RIT we have won races running an overall box reduction of 7.5 and 8.2 on two different cars. I’ve seen other teams win with reductions in double digits, overall reduction 10-14 usually. The challenge lies at the heart of the design completion as a whole. The best possible Powertrain may not be usable in our application; we don’t have the power from the motor, nor the space, manufacturing capabilities or budget. So the real trick is getting it to work in the best possible way with what we have and still being innovative along the way.

My recommendations for future work mainly involve using the imagination and innovation. I would like to see someone get higher reduction with small parts. Our packaging is so limited that your limited to smaller reductions based on size alone. I think in the future things can be more compact and more efficient by switching to side by side helical gears instead of chain driven spur gears. I would like to see someone quantify all the losses of the system and figure out where the majority of the losses are and how to decrease those losses. The most important and naïve of all my recommendations is to try something different and off the wall to just make the car go faster, after all, it is a racing application.

REFERENCES


References are limited. Because this is a project I have worked directly on and have observed and tested this investigation is a representation of the inferences I have made as well as presenting information about the technology and the unique application. Working hand in hand with the designers and lead engineers on the project I was able to gain very accurate and insightful information about the system. Because it’s a completely unique system within a broad topic there is no literature or material to reference.

ACKNOWLEDGMENTS

Special acknowledgements go to Mr. Mathew Macchione the lead Driveline Engineer for RIT Baja SAE 2008-2010. Without his insight and intimate knowledge of his system this investigation would not be possible. Also Acknowledged are Mr. Nicholas Liotta for sharing his knowledge of the system as well
as aiding me in modifying the models I used, and a special thanks to the RIT Baja SAE organization for allowing me to conduct this investigation and aiding me where ever they could.

Appendix of Figures and Data

Figure 2: Torque and HP Curve From Engine Dyno

Figure 3: Ratio selection matrix:

Figure 4: The powertrain selection matrix for the Car and the reduction data
Modern Gear Manufacturing

Iric Bressler
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
The manufacturing of gears is a series of processes that are unique to the type and quality of gear desired. Gears in general are used to transmit power from one location and transmit or transform that power to another location. Depending on the situation the gear is presented, the Cutting and finishing processes are determined. The main cutting and forming types are broaching, hobbing, milling, forging, and casting. The main finishing processes are grinding and shaving. Each of these processes are unique and will give different results depending on material used, accuracy, and luxury of processes available. The overviews of these processes are discussed. Figures correspond to the processes in order to give a visual idea of how the manufacturing processes work.

NOMENCLATURE
P = pitch
RPT = rise per tooth
n_r = number of roughing teeth
n_s = number of semi-finishing teeth
n_f = number of finishing teeth
t_r = RPT for the roughing teeth
t_s = RPT for the semi-finishing teeth
t_f = RPT for the finishing teeth

BACKGROUND
The transmission of power is the sole purpose of gears. Gears have extensive use in a countless amount of applications. Gears are used in automobiles, industrial machinery, aircraft, machining tools, and many other applications that use power to generate motion. Gears are put through strenuous operation in most applications and therefore need to have strong construction, dependable performance, high efficiency, economy and long life. Operation of these gears should involve the least amount of fatigue and high stress conditions to avoid failure. Gear drives should be effective in eliminating noise, chatter, and should ensure high load carrying capacity at a constant velocity. Gear manufacturing is a highly specialized field due to the specifications needed in all gear applications.

DESCRIPTION OF TECHNOLOGY
Gears are manufactured in many different shapes and sizes for each application. Figure 1, show the essential gear elements that need to be designed for with the application in mind. [1]

Materials used for gear manufacturing depend on the specifications of the applications. These dependencies include: type of service, peripheral speed, degree of accuracy required, method of manufacture, required dimensions, weight of the drive, allowable stress, shock resistance, and wear resistance. The material’s attributes need to satisfy many of the dependencies in order to be chosen for particular applications. Cast iron has good wearing properties, excellent machinability and ease of producing complicated shapes by the casting method while being suitable for large gears. Steel is sufficiently strong and highly resistant to wear by abrasion. Cast steel is used when the stress on the gear is high and difficult to fabricate. Carbon steels are used for most industrial gears with high toughness and high strength. Alloy steels provide high tooth strength and low tooth wear. Aluminum is used in low inertia of the rotating mass applications. Non-metallic materials provide noiseless operation at high speeds.

LITERATURE REVIEW
The history of gear manufacturing is not very cut and dry. Gears have been around since the invention of simple machines. Most early gears came in the form of wooden pegs used as cogs to turn and apparatus. The industrial revolution spiked the initial surge into metal gearing. The science of gear design
and manufacturing is a relatively 19th century phenomenon. Today, the most significant new gear developments are in the area of materials. Modern metallurgy has greatly increased the useful life of industrial and automotive gears, and consumer electronics has driven plastic gearing to new levels of lubricant-free reliability and quiet operation [1]. Today gear manufacturing is spread out between many different companies. Gear manufacturing is so broad that companies tend to specialize in certain areas and this produces a wide range of competing industries within the gear manufacturing field. In bigger industrialized areas like Rochester companies such as Gleason, develop gears and even have a broad reach outside their immediate geographical market.

OPERATION OF THE TECHNOLOGY

There are many different gear cutting processes. Each is used differently to meet the criteria of the gear needing to be manufactured. Broaching is a machining process used to cut different shapes. The tool used in the broaching process is called a broach shown in Figure 2. It has many rows of gradually increasing teeth or chisels that is passed over the part removing more material per tooth [4].

Hobbing is a machining process that involves two rotating surfaces. The gear work piece and the helical cutting tool called a hob are fed across each other while the hob makes progressive cuts into the gear blank as shown in Figure 3. This relationship is a precisely timed and proportional [4].

Milling of gears takes a longer process than hobbing. Each tooth spacing is individually cut by a rotating multiedge cutter that has a cross section similar to that of the generated teeth as shown in Figure 4. After each cut the gear blank is rotated a measured amount to start the next cut [5].

After the cutting process is complete most gears go through a finishing process. The cutting process is designed to allow for an allowance on the tooth flank for the process of finishing. Grinding is one of the most precise machining processes. The gear is typically placed on a table which would then be situated under the abrasive wheel made up of abrasives, aluminum oxide or silicon carbide as shown in Figure 5. The primary advantages for gear grinding include dimensional accuracy, improved part geometry and better surface quality. Due to the improvements from the grinding process the engineer can predict better the life of the gear [4].
Shaving is not as precise as the grinding process but still has plenty of benefits. Gear shaving produces hairlike chips. The shaver itself actually comes in a helical gear shape with special serration in the flank area of the gear teeth as shown in Figure 6. Shaving has all the same benefits as grinding does but to a lesser degree which is suitable because it is faster and less expensive [4].

Figure 6

There are other ways to produce gears without necessarily cutting them from blanks. These non-cutting processes are also known as gear forming. Gear forging is one example of a forming process. Forging is broken down into two forging types; closed die and open die. Closed die forging involves two negative images of the gear sunken into a pair of die steel blocks. The negatives are filled and clamped together to provide the energy for the deformation of the material the gear is made of as shown in Figure 7. This process may be repeated a few times in gradually increasing refinement to achieve the gear shape. After the forging the excess metal is trimmed off before finishing [6].

Figure 7

Open die forging is best described as anvil and hammer forging. An initial shape would be forged and then manipulated to specifications [6].

Gear casting is a manufacturing process by which a liquid material is usually poured into a mold, which contains a hollow cavity of the desired gear shape, and then allowed to solidify. The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process. Casting materials are usually metals or various cold setting materials that cure after mixing two or more components together; examples are epoxy, concrete, plaster and clay. Casting is most often used for making complex shapes that would be otherwise difficult or uneconomical to make by other methods [7].

THEORY OF THE TECHNOLOGY

For Broaching, the most important characteristic of a broach is the rise per tooth (RPT), which is how much material is removed by each tooth. The RPT varies for each section of the broach, which are the roughing section ($t_r$), semi-finishing section ($t_s$), and finishing section ($t_f$). The roughing teeth remove most of the material so the number of roughing teeth required dictates how long the broach is. The semi-finishing teeth provide surface finish and the finishing teeth provide the final finishing. The finishing section’s RPT ($t_f$) is usually zero so that as the first finishing teeth wear the later ones continue the sizing function [8]. All these parameters are shown in Figure 8 and 9.
For hobbing the cross-sectional shape of the hob teeth are almost the same shape as teeth of a rack gear that would be used with the finished product. There are slight changes to the shape for generating purposes, such as extending the hob's tooth length (pitch) to create a clearance in the gear's roots [8]. The dimensions of the hob are shown in Figure 10.

The milling process begins with the chip thickness at zero and increases up to the maximum. The tool slides across the surface of the material, until sufficient pressure is built up and the tooth suddenly bites and begins to cut as shown in Figure 11. The sliding and biting behavior leaves a poor finish on the material therefore leaving the part in need of finishing.

Gear Grinding machines are power driven at a required speed which is determined by the diameter of the grinder and the speed at which it grinds. Substantial amount of heat may be produced while grinding depending on the gradient of the grind being performed. A coolant is then applied to keep the heat low in order to not warp the part. Grinding machines can be set to a very high precision, up to 200nm per pass. Traditional gear shaving is done in the parallel to the gear axis. The tool and gear are pressed together and ran by each other as shown in Figure 12.

Forging depends on the material properties. Most forging is dependent upon the recrystalization temperature of the gear material [8]. Figure 13 shows two scenarios of how a forged material changes shape when pressure and/or temperature is applied.
Casting quality is dependent on the cooling of the material set in the cast. The most important part of the cooling curve is the cooling rate which affects the microstructure and properties [8]. Figure 14 is an example cooling curve of a metal.

DISCUSSION
The future of gear manufacturing lies in automation. Automated processes take out the inaccuracy of human touch and create extremely small tolerances for gears. All gear manufacturing processes are now automated in some way. In order to improve on the automated process the component handling side of the manufacturing process can be advanced. The accuracy of each component from handling of the gear to the cutting process to the finishing process can be exacted to a smaller tolerance therefore creating a highly specialized and optimum gear for each scenario the gear will be placed in.

CONCLUSIONS AND RECOMMENDATIONS
The future of gear manufacturing, I don’t believe, will include radical changes but include drastic improvements on the individual steps throughout the manufacturing process. I also see a significant opportunity to improve materials wise in gear manufacturing. Material sciences can improve gear manufacturing significantly in the material the gear is made up of, the material and hardness of the cutter whether broaching, hobbing or milling, and even the weight of the materials used in machining the gears can make the gear manufacturing process improve.

REFERENCES
THEORY AND OPERATION OF PROTON EXCHANGE MEMBRANE FUEL CELLS

Conley Brodziak
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
Fuel cells vehicles (FCV) require a completely different powertrain system than internal combustion engine vehicles (ICE). A typical ICE has efficiencies on the order of 18 to 20 percent at best, while the proton exchange membrane fuel cell (PEMFC) has efficiencies near 50 to 70 percent. Though, after accounting for all other losses to keep the system in working order, efficiencies of the system are around 30 to 50 percent with a bias towards the lower end. As a result of this higher efficiency, the options for, and advancements in the powertrain of a PEMFC vehicle are analyzed in this paper.

The system as a whole has very few moving parts to transfer the power generated to the various components of the vehicle. Moving parts as well as non-moving parts will be analyzed with regard to what they accomplish, their necessity to the system as a whole, efficiency effects, and cost.

Improvements over the past 10 years or so, mainly in the manufacture of fuel cells, have made quite a difference in the development and the wish to pursue the benefits of a low emission and quiet power generating system. Bipolar plate material and more precise production of the plates, along with electrolyte material, reduction in amount of platinum used as the catalyst on the anodes and cathodes, and inventions such as regenerative braking and the thermoelectric, outline such improvements. Despite these advances, a long road exists ahead before the PEM fuel cell vehicle enters mass production.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCV</td>
<td>Fuel Cell Vehicle</td>
<td></td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
<td></td>
</tr>
<tr>
<td>PEMFC</td>
<td>PEM Fuel Cell</td>
<td></td>
</tr>
<tr>
<td>PEM</td>
<td>Proton Exchange Membrane</td>
<td></td>
</tr>
<tr>
<td>BLDC</td>
<td>Brushless Direct Current</td>
<td></td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
<td></td>
</tr>
<tr>
<td>BoP</td>
<td>Balance of Plant</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Voltage</td>
<td>(Volts)</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
<td>(Watts)</td>
</tr>
</tbody>
</table>

Greek Symbols

$\eta$ Efficiency
$\mu$ Proportion of utilization

Subscripts

e electric
c of an individual cell
2 two atoms
f fuel

BACKGROUND
The development of the FCV is crucial to sustainability. As of right now, the world is consuming fossil fuels at a rate faster than nature can replenish the supply and can rid the bi-products out of the air. Not only is the FCV sustainable (given that the hydrogen is produced by sustainable means), it is also more efficient than the ICE.

America also needs to decrease its dependence on foreign oil in order to not succumb to the growing power of those that dictate the price. Capitalism must regain its businesses in America and put the average citizen back to work creating his and her own energy. Once the market accepts the FCV as a viable and feasible alternative to the ICE, the capitalistic nature that made this country a superpower will once again put America at the leading edge of the improvement in living and wealth.

As hinted earlier, the way through which hydrogen is obtained is most crucial to this breakaway from dependence on oil. Along-side the advancements of the FCV need to be advancements in solar, wind and hydro (from waterfalls and dams) energy. Fundamentally, hydrogen should be a means by which these three other energies are stored for portable and easy usage.

While the theory of reverse electrolysis of water has been around for quite some time, improvements in its efficiency have not been made until the past 15 years. Since then, almost every major car manufacturer has begun work in researching and improving the powertrain of the hydrogen FCV. Companies have already started putting these vehicles on the road in small numbers in order to gain attention and spark the creation of hydrogen.
production and distribution facilities. Infrastructure has placed a great damper on the development of different sources of energy. This is similar to asking which came first, the chicken or the egg? Hydrogen production companies do not want to start building refueling stations without any cars; meanwhile car companies do not want to start building cars without any way for their customers to refuel.

An alternative is an on-board fuel processing center that takes water and turns it into hydrogen to then be turned back into water. This is extremely inefficient and heavy. In order to process the water, a different source of fuel is needed, thus an onboard fuel processing center is not independent of fossil fuels which is a majority of the purpose for creating a hydrogen powered vehicle.

Reduction in cost and a foreseeable future of the FCV in the marketplace due to growing demand and interest has lead to companies that have been, and are continuing to hire recent graduates that have background in the subject area. For this reason and the reason that RIT is the icon for a sustainable world, the mechanical engineering department has added courses in fuel cell systems research. The research extends beyond use in vehicles. Fuel cells can generate anywhere from 1 Watt to 100 Mega Watts of power. Thus, they can be put to use for simple electronic devices such as an mp3 player, or used to generate electricity for entire buildings.

DESCRIPTION OF THE TECHNOLOGY

While the powertrain of a PEMFC vehicle has very few moving parts, operating the cell stack so as not to add undue stresses to the membranes can be quite tricky. Thus, many components are necessary. The stack itself is also quite complicated. The powertrain can be decomposed into three distinct entities; namely the fuel cell stack, components that aid in the operation of the stack, and components that send power to the wheels and other electronic devices.

Figure 1 illustrates the currently acceptable way to assemble a fuel cell stack. From now on a cell will be considered the combination of five pieces: the electrodes (anode and cathode), electrolyte, and two bipolar plates.

Figure 1: The assembly of a fuel cell stack. Taken from [1]

The anodes and cathodes are formed into rectangular sheets made from a porous composite, and then coated with a catalyst such as platinum. Gaskets are fitted around each cathode and anode sheet to prevent the leakage of hydrogen and air through the edges. Each electrode is placed on opposite sides of a sheet of an electrolytic material, usually fluoroethelyne such as Nafion® (DuPont). The three sections are pressed together between opposing bipolar plates. A typical vehicle requires about 70 cells to be stacked together in series in order to meet the power requirements. The combination of all cells will from now on be referred to as the fuel cell stack.

Each of the following parts may be connected to the fuel cell stack, but are not always necessary. Figure 2 illustrates these parts.

Figure 2: General connection of useful parts to keep the fuel cell stack from experiencing large and repeated stresses. Adapted from [2]

First of all, the fuel cell stack needs the fuel. There are two parts to the fuel, namely, the hydrogen 1 and the reactant air 2. The hydrogen 1 is forced through the channels in the bipolar plates (not shown in Figure 2 for simplicity) via the hydrogen
circulation pump 3. The reactant air 2 is forced through the opposite bipolar plate (also not shown in Figure 2) via the blower 4. Before the reactant air 2 is allowed to reach the cathode 5, it must pass through a humidifier 6 which allows moisture from the exit air 7 to pass through a membrane. Hydrogen 1 that was not consumed on its journey through the anode 8 passes through a trap 9 before being re-circulated through the cell stack. An ejector circulator (not pictured) can be used to harness the mechanical energy stored within the compressed hydrogen to push the unused portion back through again. A turbocharger (also not pictured) which has no moving parts can be used to recapture some of the energy lost by way of heat from the exit air. The turbo charger runs off of a turbine which is connected on the same shaft as a generator. For larger systems (usually larger than a few kilowatts), water or coolant 10 is needed to cool the fuel cell stack. This is accomplished by adding a water pump 11 and a radiator 12 to move the water through separate channels in the bipolar plates. A typical fuel cell used in automotive applications should be kept at about 2 bars of pressure. Thus, each connection hose/pipe must withstand its associated pressure.

The third subsection of the powertrain includes the components responsible for delivering the power to the wheels and other electronics such as electronic stability control. Figure 3 displays these components.

Figure 3: General connection of parts necessary for the delivery of power to the wheels and other electronic devices. Taken from [2]

A power conditioner 13, such as a DC/DC converter, is absolutely necessary to clean up the voltage, and thusly the current produced by the fuel cell stack 14. This current is then fed to however many BLDC motors 15 are needed to drive the wheels of the car. This will vary on the type of vehicle. To assist the fuel cell during transient conditions which occur frequently while operating a vehicle, a supercapacitor 16 may be connected in parallel with the fuel cell stack 14. Also shown in Figure 3 are any other ancillary devices 17 which are connected to charge the supercapacitor 16. These can be thermoelectric modules or a regenerative braking system, or anything else that aids in reclaiming energy lost to the surroundings. Lastly, some DC/AC inverters 18 located after the power conditioner 13 may be necessary to drive other electronic components.

LITERATURE REVIEW

Reverse electrolysis was first discovered by Christian Friedrich Schönbein in 1838 and then demonstrated by Sir William Robert Grove in 1839 who published his findings in the Philosophical Magazine and Journal of Science [3]. For a while, no notable advancements were made with the fuel cell until W. Thomas Grubb and Leonard Niedrach (both while working for General Electric) made two important discoveries.

Grubb realized in 1955 that using a sulphonated polystyrene ion-exchange membrane as the electrolyte enhanced the flow of ions from the anode to the cathode. Niedrach discovered a great way of applying platinum to the membrane in 1958. The result was the “Grubb-Niedrach fuel cell” which was developed further and used during Project Gemini. Grubb acquired 26 patents during his career at GE and was known as the expert of fuel cells [Schenectady]. Niedrach also had many patents including one titled Electrode Structure and Fuel Cell Incorporating the Same which describes how sheets of electrodes and electrolytes are efficient for diffusion of the gases [4].

Francis Thomas Bacon was also a huge proponent of the fuel cell. He, along with the help of Marshall of Cambridge Ltd. demonstrated publicly a 5 kW, forty-cell battery which operated with 60 percent efficiency. Pratt and Whitney obtained the patent and used the fuel cell on Project Apollo.

Roger Billings developed the first hydrogen fuel cell automobile in 1991 and founded Billings Corp which deals in hydrogen energy research and computer networking [5].

OPERATION OF THE TECHNOLOGY

Hydrogen is stored either in pressurized tanks, as liquid hydrogen, or by chemical methods such as in metal hydrides. Storing hydrogen in pressurized tanks is most effective and cost efficient. Liquid hydrogen must be kept very cold and thus requires energy to maintain its temperature. While the hydrogen is pressurized in tanks, the biggest concern is the weight and not the combustive nature of the gas.

The hydrogen is pumped through lines that carry it to the fuel cell stack where it enters one side of the bipolar plate, travels through the grooves and diffuses through the anode. The hydrogen entering
must be near 100 percent humidity in order to not dry out the anode. Keep in mind that hydrogen is diatomic so it comes in pairs. At the anode, two hydrogen atoms split to form four hydrogen protons and four electrons. The protons travel through the electrolyte to the cathode. While going through the electrolyte, each proton can carry up to 5 water molecules with it which can flood the cathode and dry out the anode. For this reason, a mostly hydrophobic membrane Nafion was developed. The four protons combine with oxygen (another diatomic) and four electrons, which just traveled as a current from one bipolar plate to the next, to form water.

The warm water vapor coming out of the cathode, which is near 100 percent humidity but not over, flows through the humidifier to humidify the incoming reactant air. The humidifier consists of two channels with a membrane in between to allow for the exchange of vapor. This membrane can be stationary but is often constantly rotating in order to flip the vapor from one side to the other. Unused hydrogen passes through a trap to prevent any dirt from being re-circulated as it makes its way through the fuel cell again. The ejector circulator uses the mechanical energy stored in the compressed hydrogen to draw excess hydrogen from the exit stream after it goes through the trap.

Electricity travels from one bipolar plate to the next. Because the plates are bipolar and thin, the electrons do not have to permeate through an entire plate to get to a wire that then goes to another plate. Bipolar plates reduce internal resistance incredibly and thus increase the current density. Current density is typically rated in Amps per square centimeter. The electricity is sent through a power conditioner which cleans up the voltage and current into a nice signal. These can be voltage regulators or DC/DC converters.

Various voltage regulators can be used in fuel cell vehicles including the metal oxide semiconductor field effect transistor (MOSFET), or the insulated gate bipolar transistor (IGBT), or a simple gate-turn-off thyristor. The type of regulator used does not, however, affect the ultimate performance of the fuel cell vehicle or the purity of the voltage delivered to the various motors [FCT]. Inverters may also be necessary to supply certain components that require alternating current. In order to abstain from high frequency harmonics which can impart harmful effects on critical system components, a smooth current characterized by a sine wave is ideal. Obtaining an alternating current that is sinusoidal in nature is solved to a good approximation by using a pulse width modulation or a tolerance-band pulse-inverter [6]. The description of how power inverters/converters work is beyond the scope of this paper.

Current is thus sent to the brushless direct current (BLDC) motors that drive the vehicle. These motors are brushless to avoid sparks. Spark avoidance is important because if there is any leak in the fuel cell stack or the tanks for any reason, then the hydrogen can ignite and cause an explosion. BLDC motors provide long lifespan, are low maintenance, have high efficiency and can deliver the torque needed to move the vehicle [7].

THEORY OF THE TECHNOLOGY

The basic reaction that takes place is in accordance with Equation 1 shown below. Hydrogen and oxygen combine to form water.

\[ 2H_2 + O_2 \rightarrow 2H_2O \]

Equation 1: Basic reaction that occurs.

In reality what happens at the anode follows Equation 2, and what happens at the cathode follows Equation 3. The hydrogen protons travel through the electrolyte to the cathode while the electrons travel through the bipolar plates.

\[ 2H_2 \rightarrow 4H^+ + 4e^- \]

Equation 2: Reaction at the anode.

\[ O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \]

Equation 3: Reaction at the cathode.

A well designed fuel cell stack with about 70 cells operating at about 90 °C and 2 bar of pressure can generally create about 10 kW of power. This is enough power to move a small vehicle. For larger vehicles such as busses, over 200 kW of power are needed. This means that perhaps several fuel cell stacks are needed along with large cooling capabilities and large pumps. When a fuel cell is quoted at a certain number of kilowatts, that number relates to only about half of the energy produced according to Equation 4. The rest of the energy produced is wasted thermally.

\[ \text{Heating Rate} = P_c\left(\frac{1.25}{V_c} - 1\right) \]

Equation 4: Heating rate of a typical fuel cell (measured in Watts). Taken from [2]

Each cell inside the stack produces about 0.7 Volts (with a useful current which is why the cells need to be connected in series. As mentioned before,
usage of fuel cells can range from 1 Watt (.0013hp) to 100 Mega Watts (13,400hp).

70 cells in a stack might seem like a lot, but each cell is not very thick at all. In fact the thinner each bipolar plate, electrode, and electrolyte, the less internal resistance on the current. The Nafion electrolyte used today is on the order of about 50 micro-meters (.002 in) thick. Nafion is actually a polytetrafluoroethylene (PTFE) that is similar to Teflon with sulphonic acids attached to the ends. Because it is so thin, the temperatures at which it can operate are limited. While the cell can start and run “cold”, the warmer it gets, the higher the current density because heat acts as a catalyst. However, the Nafion should not exceed 85 °C [8]. The platinum that is sandwiched in between the electrodes and the electrolyte used to be applied in quantities of 32 milligrams per square centimeter (.0073 oz per square inch). This used to make the cells very expensive. Manufacturers are now able to cut that amount down to about .2 milligrams per square centimeter (4.6 X10⁻⁵oz per square inch). This used to make the cells very expensive. Manufacturers are now able to cut that amount down to about .2 milligrams per square centimeter (4.6 X10⁻⁵oz per square inch).

The maximum efficiency of the fuel cell stack relates to the Gibbs free energy which is “energy available to do external work, neglecting any work done by changes in pressure and/or volume” [2]. Equation 5 gives the maximum efficiency allowed where \(\Delta g_f\) is the average free energy of the products minus that of the reactants and \(\Delta h_f\) is the change in enthalpy of formation.

\[
\eta_{\text{max}} = \frac{\Delta g_f}{\Delta h_f} \times 100
\]

Equation 5: Maximum energy allowed according to Gibbs free energy. [2]

While this is nice to know, the actual efficiency of the fuel cell stack is related to the voltage of a single fuel cell and the fuel utilization. Fuel utilization is typically around 0.95 Equation 6 gives the actually efficiency.

\[
\eta = \frac{V_c}{1.48} \times 100
\]

Equation 6: Actual efficiency. [2]

If used to power busses and other large vehicles, a fuel cell stack will most likely contain a turbocharger to regain some of the energy lost thermally. These turbochargers can often produce 50KW (67 hp) of power.

As mentioned earlier, when using a PEMFC in a car, pressure should typically be around 2 bar or between 1 and 8 atmospheres. Higher pressure means higher power densities which is necessary if using surrounding air as the reactant instead of pure oxygen. Most vehicles operate on surrounding air. High and equal pressures on either side of the cell helps to reduce gas cross over and hydraulic permeation [9]. Despite the gaskets around the electrodes, hydrogen and oxygen can leak out and mix together outside and produce undesirable effects. Storage of hydrogen fuel can either be in the form of liquid hydrogen, chemically stored hydrogen or in pressurized tanks. If pressurized tanks are to be used, which is most common, the tanks are pressurized around 450 bar[9]. A medium sized tank at this pressure can store about 1kg (2.2lb) of hydrogen gas, but takes about 40 to 50 liters (1.4 to 1.75 cubic feet) of space. Because hydrogen is lighter than air, the tanks should be stored on the roof of the vehicle in case of a leak.

**DISCUSSION**

The PEMFC is on its way to becoming a viable alternative to ICE’s. Slowly but surely more hydrogen production and distribution facilities are opening across America. This is in part due to the automotive industry investing heavily in getting vehicles out on the road and marketing the new technology. Investments should be made in PEMFC technology today to secure a financial stronghold a couple of decades in the future.

Development still needs to be made especially with regard to the bipolar plates. Their durability and cost are not acceptable to today’s driver. The average vehicle is expected to last for about 5,000 hours. With the stresses and strains on such thin components, there exists ample opportunity for the fuel cell stack to fail. The bipolar plates need to be analyzed more to determine the best paths by which to move the fluid to the electrodes and to ventilate and cool the system.

As mentioned earlier, this technology should only develop at the same time as wind, solar, and hydro energy. Hydrogen fuel should be developed only as a means to store these other three energies for portable use. The green initiative has pushed companies around America to start giving this technology considerable thought.

Using fossil fuels or any other sources than the three mentioned is irresponsible. Nothing is 100 percent efficient, thus the more times energy is transformed from one substance into another, the less efficient the whole system becomes. Just because a vehicle does not produce any emissions doesn’t mean that it is okay to make the hydrogen through electrolysis by using fossil fuels. In fact because of inefficiencies, more fossil fuels are consumed to
obtain the same results from hydrogen as would be seen by using the fossil fuel directly.

REFERENCES
THEORY AND OPERATION OF A TWO-MODE HYBRID ELECTRO-MECHANICAL TRANSMISSION

Philipp K. Buchling
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
The objective of this paper is to investigate and analyze the theory and operation of a two mode, compound split, hybrid electro-mechanical transmission. The model that will be investigated and analyzed is one that is suited for implementation and efficient use in small trucks and other such vehicles where fuel-efficiency is a concern, along with high power and torque output, and vehicles characterized by duty cycles that require a continuous, constant speed operation at high-average velocities. A two-mode hybrid transmission provides several advantages over conventional automatic transmission. These advantages include improved fuel economy and high performance, thanks to the combination of power received from an internal combustion engine and two electric motor/generators. In particular, the transmission model that will be investigated is the one described in U.S. Patent No. 5,558,589 by Schmidt [1], issued to General Motors on Sept. 24, 1996, and represents one of the first transmissions of this type.

The advantage of the two mode electro-mechanical transmission here analyzed over different hybrid transmissions, is that it will deliver high fuel-efficiency and for low-average duty cycles (such as start/stop duty cycles in inner-city driving), along with sustained fuel-efficiency and high power for high-average duty cycles (such as highway driving or towing). This can be achieved in a number of different ways, but in the transmission here analyzed, it is accomplished by means of a compound planetary gear set with two planetary gear sub-sets (each with a sun gear, planet carrier, ring gear, and several planet gears), three torque transfer devices, two electric motor/generators, and an electric energy storage device.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Horsepower</td>
<td>(HP)</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
<td>(Nm or ft-lbf)</td>
</tr>
<tr>
<td>e</td>
<td>Gear ratio, or train value</td>
<td>(#)</td>
</tr>
<tr>
<td>N</td>
<td>Number of gear teeth</td>
<td>(#)</td>
</tr>
</tbody>
</table>

Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega )</td>
<td>Rotational Speed</td>
<td>(RPM)</td>
</tr>
</tbody>
</table>

Subscripts & Superscripts

- \( s \) Sun Gear
- \( r \) Ring Gear
- \( s1 \) Sun Gear, first planetary gear sub-set
- \( s2 \) Sun Gear, second planetary gear sub-set
- \( c1 \) Planet Carrier, first sub-set
- \( c2 \) Planet Carrier, second sub-set
- \( r1 \) Ring Gear, first sub-set
- \( r2 \) Ring Gear, second sub-set
- \( \text{in} \) Input
- \( \text{out} \) Output

BACKGROUND
Hybrid vehicles are becoming increasingly popular around the world, as gas prices continue to rise. There has also been significant development of electric vehicles, which could very well become the way of the future as technological advances allow experts in the field to develop more efficient, powerful, and reliable electric cars. However, a conversion to fully electric vehicles may still be decades away for larger vehicles such as trucks and public transportation vehicles. There may be a transition to hybrid trucks and buses in the near future, as fuel efficiency becomes increasingly important to consumers. Recently, a number of different auto-makers began developing hybrid transmissions for small trucks, in an effort to deliver high power and torque in a fuel-efficient manner. This new direction for hybrid transmissions came to be when General Motors, DaimlerChrysler and BMW joined forces to form the Global Hybrid Cooperation. They began to develop so-called “two-mode” hybrid transmissions, in which there are two modes of operation that occur at different vehicle speeds, thus providing high fuel efficiency at all speed ranges, combined with high torque and power capabilities, as an internal combustion engine and two electric motor/generators work together.

The two modes in this hybrid electro-mechanical transmission signify that there are two gear trains through which power is transmitted, or two modes of operation. As stated by Schmidt, M., “Operation in the first or second mode may be selectively achieved by using torque transfer devices. In one mode, the output speed of the transmission is proportional to the speed of one motor/generator, and
in the second mode the output speed of the transmission is generally proportional to the speed of the other motor/generator.” [1]

The two-mode, hybrid electro-mechanical transmission in question is compound split, that is, the different sources of power (from the internal combustion engine, and each of the electric motor/generators) are separated onto distinct shafts of their own, operatively connected to the transmission, and then to the output shaft. In this manner, in each of the two modes of operation, which will be described in full detail later on, one of the two motor/generators can be at a mechanical point, or stationary, such that no power is wasted in driving both of the motor/generators, as this drastically reduces the efficiency of the transmission and effective power output. The existence of more than one mechanical point for one of the motor/generators is beneficial since the maximum mechanical efficiency occurs at this point. Some hybrid transmissions with more than one electric motor suffer from such efficiency losses as there is no way of disconnecting either of the motor/generators from receiving power. This presents another advantage of the present transmission over other hybrid transmissions.

Furthermore, a higher overall mechanical efficiency is achieved with this arrangement than, for example, in a series hybrid transmission. In series hybrid transmissions, power flows from an engine to a battery, then to an electric motor, and then finally to the output shaft. Throughout all of these energy conversions there is inevitably a significant amount of power loss. The compound split arrangement used in this hybrid transmission means this unilateral flow of power is no longer necessary, and power losses are thus greatly reduced in comparison to the series arrangement.

In the present two-mode hybrid transmission, if the on-board computer determines that speed requirements are low, the internal combustion engine can be completely disengaged and the vehicle be run solely on the power of one of the electric motor/generators. This effectively extends the range of the vehicle. If the on-board computer should determine that power requirements are high, then the internal combustion engine can supply power and be aided by one, or both, of the electric motor/generators resulting in an increased power output. This allows for a reduced dependency on the internal combustion engine alone, increasing fuel-efficiency even in situations where a higher amount of power is required, and results in an overall increase in power and torque.

The mounting of the electric motor/generators on separate shafts allows for a simple method of supplying power to the motor/generators separately, and effectively running them in reverse as generators when the on-board computer deems it necessary. This is convenient as both motor/generators are connected to a common battery (or other electric energy storage device), such that charging of the battery can be readily performed from either of the motor/generators.

The use of torque transfer devices, in combination with electric motor/generators, and a compound planetary gear set allows for a variety of speed and torque output combinations, which is especially beneficial for the purpose of fuel-efficiency in a hybrid transmission such as this one. As will become evident later on, this combination produces a transmission whose output is effectively continuously variable, i.e. an electric variable transmission (EVT), or electronic continuously variable transmission (e-CVT).

This transmission in particular was patented in 1996, and there have been numerous developments since then. The most recent embodiments of these two-mode hybrid transmissions, such as U.S. Patent No. 5,931,757, which issued on Aug. 3, 1999, to General Motors Corporation, and U.S. Patent No. 6,953,409, which issued on Oct. 11, 2005, to General Motors Corporation, feature several fixed gear ratios, that can combine with the electric motors to produce a continuously variable output. Additionally, these transmissions feature a lock-up clutch which allows for a quick shift to maximum power output. Furthermore, the newer versions feature the electric motor/generators arranged coaxially, circumscribing the planetary gear sets, thus solving several packaging issues of the present transmission. Effectively, this results in the possibility of simply replacing the standard transmission in a small truck with the two-mode hybrid transmission, with no further modifications to the vehicle. [2] [3] In both the older and newer versions of the transmission, the internal combustion engine is managed in order to produce a constant, optimal speed (RPM) output to maximize fuel-efficiency.

The characteristics of this hybrid transmission make it ideally suited for small trucks, where fuel-efficiency and good power and torque output are an important consideration. Furthermore, a design such as this one would provide a good basis for trucks in the next few decades, where regulations concerning vehicle emissions could potentially become more restrictive, or gasoline prices could further increase. This transmission design could therefore offset the potentially increased cost of driving a truck in the next decade. Additionally, it could provide environmentally concerned individuals with an option to purchase a larger vehicle without sacrificing power or utility for a smaller hybrid vehicle.

**DESCRIPTION OF THE TECHNOLOGY**

A two-mode hybrid electro-mechanical transmission is characterized by the fact that there are two gear trains, or modes, available for an on-board computer to selectively engage. The computer decides,
according to the operator inputs received, to transmit power from the engine, one of the electric motor/generators, or both, to the output shaft. In a compound split, hybrid electro-mechanical transmission, there is more than one source from which power is delivered to the output shaft.

FIG. 1 shows a diagram of the transmission, and what follows is a step-by-step description of the numbered transmission components depicted, following the description provided by Schmidt [1].

“The compound planetary gear set 20 includes first and second planetary gear sub-sets 22 and 24. The first planetary gear sub-set 22 has an outer gear member 26, generally designated as the ring gear, which circumscribes an inner gear member 28, generally designated as the sun gear. A plurality of planet gear members 30 are rotatably mounted on a carrier 32 such that each planet gear member 30 meshingly engages both the outer gear member 26 and the inner gear member 28.” [1]

“The second planetary gear sub-set 24 also has an outer gear member 34, generally designated as the ring gear, which circumscribes an inner gear member 36, generally designated as the sun gear. A plurality of planet gear members 38 are rotatably mounted on carrier 40 such that each planet gear 38 meshingly engages both the outer gear member 34 and the inner gear member 36.” [1]

The ring gear 26 of the first planetary gear sub-set 22 is connected, via a sleeve shaft 42, to the carrier 40 of the second planetary gear sub-set 24. Furthermore, the carrier 32 of the first planetary gear sub-set 22 is connected, by means of another sleeve shaft 46, to the ring gear 34 of the second planetary gear sub-set 24. “The carrier 32 of the first planetary gear sub-set 22 is connected to a transmission drive shaft 50. The transmission drive shaft 50 is connected to an output shaft 52, as through a first torque transfer device 54...” [1]

“The inner gear member 36 of the second planetary gear sub-set 24 [...] is connected to a third sleeve shaft 68 that terminates in a transfer gear member 70 that meshingly engages a first connecting gear member 72. The first connecting gear member 72 is connected to a second connecting gear member 74 through the second torque transfer device 66. The second connecting gear member 74 meshingly engages a drive gear 76 that is affixed to the output shaft 52. It will be noted that the hub portion 78 of the drive gear 76 may be connected to the first torque transfer device 54.” [1]

The input shaft 12 from the internal combustion engine can be connected to the ring gear 26 of the first planetary gear sub-set 22 by means of another torque transfer device 80, acting as a clutch.

The first electric motor/generator 88, is connected to a drive gear 92 via a shaft 94. Said drive gear 92 meshes with an idler gear 96, which is itself connected to another connecting gear 98 that is secured to the end of sleeve shaft 100. “The other end of the sleeve shaft 100 is secured to the inner gear member 28 of the first planetary gear sub-set 22.” [1]

The aforementioned connecting gear member 72 is also connected to a drive gear 102, which is powered by the second electric motor/generator 90 by means of shaft 104. In this manner the second motor/generator 90 is operatively connected to the sun gear 36 of the second planetary gear sub-set 24.

Thanks to the connection of the first and second electric motor/generators 88 and 90 to separate members of the first and second planetary gear sub-sets, 22 and 24, receiving power from the engine 14, in combination with the three aforementioned torque transfer devices, 54, 66, and 80, an electric variable transmission or EVT is produced.

Evidently, as can be seen in FIG. 1, there are some significant space and packaging issues with this transmission as compared to a conventional automatic transmission. This is most significantly due to the size and positioning of the two electric motor/generators 88 and 90. Their situation such as it is in this design prevents this transmission from being implemented into an existing vehicle platform without significant revision and modification of the entire vehicle. Furthermore, the significant added weight of two electric motors, several additional shafts, and connecting gears, can lead to handling and reliability issues.

Since this patent was issued, there have been numerous developments regarding two-mode hybrid transmissions. Later versions, such as the aforementioned embodiment described in U.S. Patent No. 6,953,409 [3], feature several inter-connected planetary gear-sets, and two ring-shaped electric motor/generators now arranged coaxially, around the planetary gear-sets. FIG. 2 depicts this more recent design by Schmidt et. al. [3], and features the two electric motor/generators 56 and 72 circumscribing the planetary gear-sets. The result is a transmission that has significantly more compact packaging than the original transmission in FIG. 1, and a slight weight reduction as the extra shafts have been removed, and the design now relies only on the use of sleeve shafts, planetary gears, and torque transfer devices. The underlying concept of the design, however, remains unchanged as there are still separate input members for separate power sources.

Copyright © 2011 Rochester Institute of Technology
FIG. 1 – Adapted from [1].
LITERATURE REVIEW

Since their partnership was announced in 2005, General Motors, DaimlerChrysler, and BMW have been working together as the Global Hybrid Cooperation, with all of the engineering work occurring at the GM, DaimlerChrysler and BMW Hybrid Development Center in Troy, Michigan. According to several sources, such as Autoweek [4], the combined budget put towards development on these two-mode hybrid transmissions was at least $1 billion, with all three partners working on development of rear-wheel drive hybrid transmissions for small trucks and SUV’s, and DaimlerChrysler also working on front-wheel drive hybrid transmissions.

The development work traces back to the transmission concept analyzed in this report, based on a 1996 U.S. patent [1], but there has been significant progress on the concept since then, such as in the 1999 U.S. Patent No. 5,931,757 [2], and 2005 U.S. Patent No. 6,953,409 [3]. In these newer versions, the design features much better packaging. The result is a transmission that can replace a regular automatic transmission without any changes in production or the need for a new assembly line. The only addition to the normal vehicle platform is the larger battery pack, and the ECU which controls the sophisticated powertrain system.

Despite the progress the Global Hybrid Cooperation has made in developing two-mode hybrid transmissions, it was reported in 2009 that the partnership was due to end at the end of the year. Its termination was attributed to the cost of production of these two-mode hybrid transmissions, which was simply too high for the performance benefits it created. Certainly the economic difficulties experienced by both General Motors and Daimler-Chrysler, which separated into Daimler AG and Chrysler Group LLC in 2007 [5], did not positively contribute to the partnership either. Thus, the auto-makers promptly decided to move on to different projects of their own, although it appears that BMW AG and Daimler AG will continue their cooperation in Europe on the development of other new technologies [6].

OPERATION OF THE TECHNOLOGY

Making reference again to FIG. 1, the operation of the transmission will be described, detailing how the power received from the input shaft 12 and electric motor/generators 88 and 90 will be transmitted to the drive wheels. Mode 1:

When the ECU is commanded to accelerate the vehicle, it engages the torque transfer devices 66 and 80, but not 54. As a result, the transmission...
receives power from the input shaft 12, which transmits a torque to the ring gear 26 of the first planetary gear sub-set. This causes the sun gear 28 of the first planetary gear sub-set to rotate in the opposite direction as the other members of the first sub-set. In this manner, through sleeve shaft 100, connecting gears 98, 96, and 92, the first electric motor/generator 88 is driven as a generator. The second planetary gear sub-set is made to rotate by means of the sleeve shaft 44 which is connected to the carrier 40 of the second planetary gear sub-set. The torque is then transmitted to the planet gears 38. As a result the sun gear 36 rotates in the same direction rotates in the same direction as the input.

As torque transfer device 54 is not activated, power must flow through the connecting gear 72, and be transmitted to the output shaft 52 by means of torque transfer device 66. This allows the second electric motor/generator 90 to be run as a motor and provide additional power that is also transferred through drive gear 102 and connecting gear 72 and torque transfer device 66 to the output shaft 52. As the vehicle accelerates, the powers of the second motor/generator 90 continues to be applied to the output at an increasing number of revolutions per minute (RPM). At the same time, the first motor/generator 88 is still run as a generator, but at a decreasing number of RPM. This is depicted in FIG. 3, which shows a plot of engine speed (RPM) vs. vehicle speed (MPH). The speed of the engine is represented by line 16, the speed of the first motor/generator is represented by line 110, and the speed of the second motor/generator is represented by line 112. At point 116, the first electric motor/generator 88 reaches a mechanical point. This leads to the shift point 118 between the first and second mode. Between points 116 and 118, the first motor/generator 88 reverses its rotation to operate as a motor, and supplies power to the transmission. Operation in the second mode begins at line 120.

Mode II:

At point 118, the torque transfer device 66 is disengaged, while 54 is now activated, and both motor/generators 88 and 90 are at their maximum speeds acting as motors. With torque transfer device 54 now engaged, the engine now transmits power through the compound planetary gear-set to the output shaft 52. The first motor/generator operatively transmits power to the sun gear 28 of the first sub-set, and since torque transfer device 66 is now disengaged, the second motor/generator 90 now also powers the second sun gear 36. The speed of rotation of the two motor/generators 88 and 90, relative to the engine input transmitted to the torque transfer device 80, will transfer the desired output speed to the output shaft 52. As can be seen in FIG. 3, beyond line 120 the first motor/generator 88 decreases its rotational speed and, as the vehicle continues to accelerate, reaches another mechanical point 124. After this point 124, the first motor/generator 88 once again acts as a generator at an increasing rotational speed. At the same time, the second motor/generator 90 continues to act as a motor at a decreasing speed. Eventually it also reaches a mechanical point 126, and thus the two desired mechanical points in the second mode are achieved.

THEORY OF THE TECHNOLOGY

What follows is an analysis of the operation of the transmission in its two modes.

Mode I:

From the general equation (1) describing the relationship between planetary gear members, an expression for the output speed of the transmission in the first mode can be determined. First, an expression for the first planetary gear sub-set is found, and is shown in equation (2).

\[ \frac{N_s}{N_r} = \frac{\omega_r - \omega_c}{\omega_s - \omega_c} \]  

(1)

\[ \omega_c = \frac{N_s}{N_r} \omega_{c1} + \omega_{r1} \]  

(2)

A similar expression is determined for the output of the second stage, and is shown in equation (3).

\[ \omega_{r2} = \left( \frac{N_s}{N_r} + 1 \right) \omega_{r1} - \left( \frac{N_s}{N_r} \right) \omega_{s1} \]  

(3)

Since the planet carrier of the first planetary sub-set is connected directly to the ring gear of the second sub-set, \( \omega_{s1} = \omega_{r2} \) and the two equations are simply combined, and an expression for the output, \( \omega_{out} \) is found (4).

\[ \omega_{out} = \frac{\omega_{s1} + \left( \frac{N_r}{N_s} \right) \omega_{m}}{\left( \frac{N_s}{N_r} + 1 \right)} - \left( \frac{N_r}{N_s} \right) \omega_{m} \]  

(4)

Even though equation (4) appears to represent a constant ratio, since the output speed is transmitted to a shaft that also receives an input from the second electric motor/generator, the ratio is actually variable.

Mode II:

From the general equation (1) describing the relationship between planetary gear members, an expression for the output speed of the transmission in the second mode can be determined. As before, an expression for the first planetary gear sub-set is found
Similarly, an expression for the second planetary gear sub-set is determined, and shown in equation (6).

\[
\omega_{c1} = \left( \frac{N_s}{N_r} + 1 \right) \omega_{c1} - \left( \frac{N_s}{N_r} \right) \omega_{s1} \quad (5)
\]

\[
\omega_{c2} = \frac{\left( \frac{N_s}{N_r} \right) \omega_{s2} - \omega_{r2}}{\left( \frac{N_s}{N_r} + 1 \right)} \quad (6)
\]

These equations are combined, and solved for the output speed \( \omega_{c1} \). The solution is shown in equation (7).

\[
\omega_{c1} = \frac{\left( \frac{N_s}{N_r} \right) \omega_{s2} + \omega_{in}}{\left( \frac{N_s}{N_r} + 1 \right)} + \left( \frac{N_s}{N_r} \right) \omega_{r1} \quad (7)
\]

Equation (7) accurately reflects the fact that, since the rotational speed of the second sun gear \( s_2 \) is variable; the effective ratio of the transmission is also variable.

---

**DISCUSSION**

Although this technology provides numerous advantages from a mechanical perspective, the automakers involved in the development of two mode hybrids appear to have moved on to different projects, as the cost of producing this complicated powertrain technology is simply too high. Furthermore, despite its numerous advantages, the overall savings in fuel economy have not been very significant.

For example, according to BMW data on the X6 series, the ActiveHybrid X6, which is the two-mode hybrid version of the X6 platform, has a combined fuel consumption of 9.9L/100km (24.0 mpg); while its diesel versions have a much superior 7.4 L/100km (31.8 mpg) and 7.5 L/100km (31.4 mpg) respectively. The relatively low fuel savings as compared to the gasoline versions of the X6 (10.1L/100km and 12.5L/100km, or 23.3 mpg and 18.8 mpg respectively) simply don’t justify the enormous cost of the technology. BMW sells the ActiveHybrid for almost $10,000 more on average than regular models. In addition, the two-mode hybrid weighs on average a quarter ton more than its gasoline and diesel counterparts. That being said, the powertrain does deliver on its performance promises, as the combined power of a 400hp V8 engine and the electric motor/generators (around 80-90hp each), and combined peak torque of 780Nm, make the ActiveHybrid X6 an extremely powerful machine. [7]
CONCLUSIONS AND RECOMMENDATIONS

The two-mode hybrid transmission developed by these three auto-giants is a good example of the progress that has been made in the field of hybrid technology. Even the concept itself has evolved, as mentioned previously, to solve major packaging issues. The compound split transmission provides a number of advantages over most other hybrid transmissions. It does not require both of the electric motors to be running at all times, such as in other hybrid transmissions, it does not lose as much power in a number of different energy conversions, such as in series hybrids, and it provides a substantial increase in power and torque output at a wide range of speeds.

While one of the design’s objectives was to improve gas mileage in small trucks without sacrificing power, the actual gas mileage improvement is around 25%. Many would argue this is not enough to justify the added cost of the technology. Furthermore, due to the addition of the two electric motor/generators, there is a significant weight increase, which can lead to other issues. However, the most significant savings in fuel consumption are found in inner city driving conditions, at low speed, or stop-and-go traffic conditions. This is the area where SUV’s have historically been the weakest in terms of fuel efficiency.

The most significant benefit of the technology is actually the added power and torque output. For example, the BMW X6 ActiveHybrid delivers a peak power of 485HP and a combined peak torque of 780Nm, compared to the largest gasoline model which delivers 407HP and 600Nm. Thus, the two-mode hybrid transmission actually provides more performance improvements than improvements in fuel economy. This presents a marketing hurdle, as most people that consider purchasing a hybrid prefer a lower power, high fuel efficiency vehicle over a higher power vehicle. Similarly, people who would consider purchasing a higher performance vehicle usually would tend not purchase a hybrid vehicle.

As a result, currently there does not appear to be much of a future for this technology, since there is barely a market for it. However there is still hope for this technology, as BMW AG and Daimler AG are pursuing its implementation in luxury vehicles such as the 7-series and S-class. Furthermore, there are still possibilities for improvement of the transmission. As was accurately corrected in the newer versions, there are significant packaging improvements resulting from the positioning of the motor/generators coaxially around the planetary gears, with the added advantage of a slightly lower weight as a result of the removal of the extra shafts and gear members.

While it is not explicitly stated in the respective manufacturer catalogs whether the electric motor/generators differ from each other in design, there are some advantages to be gained if they were. Given that the first motor/generator runs mainly as a generator for most of the vehicle’s speed range, and that the second motor/generator runs mostly as a motor, the two motors could be entirely different in design. The first could be optimized for better generation properties, while the second could be designed to achieve the best performance as a motor. In future versions there could be significant performance gains from optimization of these electric motors.

Finally, this technology can be combined with several fuel-saving technologies in order to improve the overall performance of the vehicle. For example, the use of variable valve timing, and/or variable displacement technology, combined with regenerative braking, could significantly improve gas-mileage, as well as engine and brake life.

REFERENCES

ANALYSIS AND FORECAST OF OPERATIONS AT GM’S TONAWANDA POWERTRAIN FACILITY

Jeffrey Chiappone
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

In the last 10-15 years, an increase of demand for hybrid vehicles (HV’s) has shaken the foundations of the world’s largest automaker, General Motors (GM). Though an internationally renowned company, the effects of this shift in demand can be felt very close to home with one of GM’s primary engine manufacturing and assembly plants located less than 100 miles away from Rochester in the Town of Tonawanda, NY. The Tonawanda Powertrain Plant (TPT) has been in operation since 1938 and has seen drastic changes in the size of its workforce in the last decade because of changing demand in the automotive market caused by fuel efficiency concerns; with hybrid-electric technology being one of the leading topics. Because the plant has produced only internal-combustion gasoline and diesel engines over its 70+ year lifespan—most of those engines being traditionally larger “big-block” V-8’s—the future of the plant in a more environmentally-conscious world is believed to be in jeopardy.

The objective of this paper is the prediction of two possible near-future forecasts of TPT using three economic indicators over the last decade of its operations: labor size, invested capital from GM, and sales of its output. The first forecast assumes no major departure in the current operating mode of the plant in terms of type of engines manufactured, and the size and capacity of the plant. The second forecast considers the possibility of the plant undergoing a major change in operation in order to facilitate production of new and modern hybrid engines to give it a competitive edge in the current economy. Using the second forecast as the more beneficial to the area of Western New York State (WNY), the goal of this paper is the persuasion of the audience to support whatever means are necessary for this transformation from TPT from its current operation to that which is proposed in the second forecast. The methods used are the outlining of the current economy of WNY and the potential gains for the area in terms of jobs created versus taxes foregone by the City of Buffalo on new land for expanded TPT facilities.

LABOR FORCE: 2000-2011

The United Auto-Workers (UAW) Local 774 represents the hourly-paid employees at Tonawanda Powertrain. At one point in 1980 this group of GM employees once totaled as many as 14,000 [1]. By the year 2000 cutbacks, layoffs, and shrinking facilities cut that number to 3800 or less than one-third [2]. The drop in workforce did not stop here however; by as recent as March 2011 the current Japanese earthquake and tsunami caused the plant to lay off workers, bringing the latest number to just 564 total hourly workers [3]. Figure 1 shows the last decade’s decline in workforce at TPT:

![Number of Hourly Workers: Tonawanda Powertrain 2000-2010](image)

Figure 1: Labor Force of GM’s Tonawanda Powertrain plant from 2000 to 2010, in terms of number of hourly workers (trend line shown dashed). Adapted from [1]-[5], [7]-[11].

Most job losses occurred throughout history as a result of the decrease in number of vehicles that TPT’s engines were being used for, making entire production lines obsolete and thereby causing the closure of some of the plant’s buildings [4]. Other major job losses have traditionally been caused by the end in production of older, more outdated and less fuel-efficient engines such as TPT’s bread-and-butter V-8’s that it has produced almost since the end of World War II [5]. With a focus on fuel-efficiency imposed by standards such as the Corporate Average Fuel Economy (CAFE) and others from the EPA, GM can no longer afford to support such large,
heavy engines of the last generation [6]. As a result, hundreds if not thousands of TPT’s hourly-paid workforce have been put on indefinite layoff since the year 2000, as seen in Fig. 1.

**CAPITAL INVESTMENT: 2000-2010**

The second major indicator of the plant’s economic well-being is GM’s millions of capital investment in it. Contrary to the facility’s shrinking labor force, news sources and records for the Local 774 union hall point to a healthy upswing of investment into TPT since the year 2000, albeit with some fluctuations over the years. Figure 2 below examines the additional investment amounts made each year from 2000-2010:

![GM Capital Investment in Tonawanda Powertrain: 2000-2010 (Millions)](image)

The trendline shows a significant increase in capital investment made by GM into the plant—amounting to hundreds of millions—that suggests that the parent company has plans for its engine producer, especially measuring the most dramatic jump of over $800M between the years 2010 to early 2011. Furthermore, even without prior knowledge of GM’s future models or other offerings, the company has good reason to show increased investments in TPT due to a number of strong metrics on the plant’s part. Just one example of this is TPT’s repeated recognition as one of GM’s most efficient plants [7].

It is also worth noting that not only has GM been steadily increasing its investments to Tonawanda Powertrain, but the difference between current and previous amounts has also increased, in general, with 2010 being a record year with over $800M invested (the largest dollar amount invested per year to TPT in its entire history [5]). Therefore it is clear that GM is not putting the plant’s production on stand-by any time in the near future.

**SALES OF VEHICLES WITH ENGINES PRODUCED AT TONAWANDA POWERTRAIN: 2000-2010**

The third major indicator of the plant’s economic well-being is showing signs of struggling. This indicator—sales of GM vehicles using the plant’s output—measures the yearly sales of the four primary vehicle models using the engines that Tonawanda Powertrain produced during 2000-2010. According to GM’s own website of the plant, those engines are: the Ecotec 2.2L used in the Chevrolet HHR since introduction in 2005; the Ecotec 2.4L used in the Chevrolet Malibu since 2000; and the Vortec Inline 4-cylinder 2.9L and Inline 5-cylinder 3.7L, both used in the Chevrolet Colorado and GMC Canyon mid-size pickup trucks since introduction in 2004 [10]. Figure 3 details these yearly sales numbers:

![Yearly U.S. Sales of Vehicles Using Engines Made by Tonawanda Powertrain: 2000-2010](image)

It can be seen from the sales figures that the Malibu has had a few tough years but remained relatively even across the decade. The HHR and Colorado/Canyon have not, however; their numbers have declined noticeably by tens of thousands of units, almost since their respective introduction years. Autoblog lists some of the reasons behind these poor sales cited as being bad fuel economy, among others [14]. Some, like the Chevrolet Colorado are due to be replaced very soon by new models whose powertrains are currently unknown, making the contribution to these vehicles by TPT an uncertainty as well [14].

**2011-2020 FORECAST: NO CHANGE IN OPERATION**

Figures 1 and 2 show a significant disagreement between GM’s invested capital into the plant and the plant’s actual labor size every year. It becomes clear then that the plant’s strong workforce may not be being used for its true production potential; in other words the plant is producing what the
consumer market simply does not want. Even with the mild success of at least one production model to use one of TPT’s flagship engines (Chevrolet Malibu over the last decade) and the awarding of hundreds of millions of dollars, it can be seen that the decade of 2000 to 2010 had 3000 members of TPT’s workforce laid off, with the most drastic cutback occurring between the years 2000 and 2005 in which approximately 1300 workers were laid off. This clashes with that fact that during the same five-year period, over a billion dollars of investment have poured into TPT. Furthermore, plant employees have even gone on record to point at one of the most recent TPT investments towards a new V-8 engine as being a bad decision on GM’s part, mostly due to the larger cars and trucks that support them becoming obsolete—shown in Fig. 3 and Fig. 6 [4].

If GM continued making engine manufacturing decisions at TPT such as the ones it made from 2000-2010, it stands to reason that operations of the plant from 2011-2020 will continue in the same manner as what was shown from 2000-2010. This can be modeled with a regression analysis run on the 2000-2010 data from Fig. 1, in order to determine the linear relationship and thereby forecast the next decade of expected labor data for the plant. This forecast data is shown in Fig. 4. If the linear trend were extended to the year 2020, it can be shown that the current workforce will decline even further to only 362 hourly workers by the year 2015 and to as little as 157 hourly workers by the year 2020, meaning 466 additional jobs lost throughout the next ten years, or 74.8% of their 2010 work force. For a plant that has the capacity to have housed 14,000 hourly workers decades ago, a labor force of only 157 will be pushing the boundary for keeping the plant open while it continues to cost GM significant operational costs for power, among other things. Therefore, closure would certainly be in the plant’s very near future.

![Figure 4: Forecast of number of hourly workers each year during the period of 2011-2020, adapted from regression analysis of Fig. 1 data.](image)

### 2011-2020 FORECAST: SHIFT TOWARDS HYBRID ENGINE PRODUCTION

The environmental and socio-political issues responsible for the major increase in demand of hybrid vehicles from 2000-2010 include most advertising campaigns by major automakers sold in the United States. Nearly every auto advertisement includes persuasive information on the particular vehicle’s fuel efficiency as well as a quantitative or qualitative comparison between that vehicle and other competitors in its class. Negative media attention surrounds global warming as a result of carbon-dioxide from the burning of fossil fuels in automobiles—another of the various issues impacting the demand for hybrid vehicles versus that of other vehicles. This has raised awareness of the future of the petroleum-based auto industry and the possibility of alternative fuel sources, a digression away from the very gasoline and diesel engines that Tonawanda Powertrain has been relying on since the 1930’s. Lastly, wars and political turmoil in regions rich in crude oil such as the Middle East have historically raised the average price of petroleum-based fuel in the United States. Figure 5 shows the average gasoline price at the end of each year, as adapted by Wolfram Alpha and sourced from the United States Energy Information Administration [26]. In all of these issues, the common bond is that attention is being turned away from traditional automobile fuel sources and instead towards alternative sources, specifically electricity.

![Figure 5: Average price per gallon of regular gasoline every November from 2000-2010 (trend line shown dashed). Adapted from [22].](image)

Automobiles using alternative fuel sources have been available in the United States since the very beginning of the 2000-2010 period, beginning with the Toyota Prius [15]. Domestically, however, GM has only produced hybrid vehicles since 2005, beginning with the GMC Sierra hybrid pickup truck [24]. Rather than the GMC pickup, a closer
competitor to the Prius (due to its size and class) would be the gas-electric hybrid car from Chevrolet, the Volt. Although adequate sales figures are not yet available for the Volt, which debuted in December 2010, a sense of the difference in demand for hybrid vehicles versus those of traditional internal-combustion engines can be seen in an investigation of the sales of the Prius and another Toyota vehicle, the full-sized sport utility vehicle Sequoia. Figure 6 shows annual sales figures for that manufacturer’s gas-electric hybrid Prius and full-size sport-utility vehicle (SUV) Sequoia from 2000-2010. Additionally the 2000-2010 sales of the Chevrolet Malibu, whose engine is produced by Tonawanda Powertrain, are compared on the same figure.

Figure 6: Annual U.S. sales for Toyota Prius and Sequoia, and Chevrolet Malibu: 2000-2010

There is clear indication in these sales figures that even under a historically successful auto manufacturer such as Toyota, sales of some vehicles can suffer in response to those popular environmental and socio-political issues previously mentioned—while other vehicles prosper as a result. In Fig. 6 the only vehicle showing a steadily increasing trend in sales is the Toyota Prius which has the highest fuel efficiency of the three vehicles at any year, according to the Environmental Protection Agency (EPA), of a maximum of 50 miles-per-gallon [21]. The sharpest decline in Prius sales can be observed from 2007-2009 and may be influenced by the downturn in the world economy at that time, however even in the last two years of its sales there are slight but meaningful increases.

Looking back at the Chevrolet Volt, monthly sales since its debut in December 2010 have been steady at around 300 units per month, with a large increase from 281 units sold in February 2011 to 608 units sold in March 2011—a positive indicator of future sales [29-33]. If yearly sales of the Volt are forecast according to the trend of the Toyota Prius, GM can expect an increase to as many as 140,000 units sold each year beginning in 2020, nearly matching the best sales of the Malibu, a model that has been around for decades longer by comparison (referenced from Fig. 6).

These forecast sales could have been a success for Tonawanda Powertrain, but GM made the decision to produce the Volt’s engines in Flint, Michigan. More details about that decision reveal that Volt engine production would be carried out at an existing plant in Flint instead of GM building an entirely new plant [23]. GM found that rather than spend $370 Million on a new facility, it could instead save $120 Million by simply retooling an existing Flint facility for $250 Million and bring it to the level that is required to produce Volt engines. That amount spent on retooling is slightly larger than one-quarter of the total amount spent by GM on the Tonawanda Powertrain plant in 2010 alone (Fig. 2). With half of that investment going primarily towards a new V8 engine model for larger SUV’s and pickups, it is unclear of how much GM will get out of its investment since comparable vehicles such as its Colorado/Canyon are showing declining sales, as well as those of Toyota’s Sequoia (Figs. 3, 6). Additionally, in the year preceding the debut of the Chevrolet Colorado/GMC Canyon, for example, over $300 Million was invested into Tonawanda Powertrain to prepare it for a vehicle that GM assumed would be successful (Fig. 2).

WHAT GM NEEDS TO DECIDE

As demonstrated in the possible forecast shown in Section VI above, what Tonawanda Powertrain needs is for GM to re-focus its production towards the kind of modern vehicles that are showing positive trends. Although the Volt’s engine production is currently earmarked for Flint, Michigan, an increase in its popularity could cause a need for more production facilities, making Tonawanda Powertrain—with its historically well-known efficiency—a prime candidate [7]. In comparison, Toyota’s Motor Manufacturing Kentucky plant in Georgetown, Kentucky (TMMK) has shown to have a much stronger grasp on its workforce during the volatile automobile decade of 2000-2010 (alternately, Prius engines are produced exclusively in Japan at the time of writing this paper, but for market similarity only American facilities will be compared in this paper [34]). Figure 7 shows the yearly number of hourly employees at TMMK:
TMMK lost a maximum of only 1200 employees over this period, or about 15.4% of their year-2000 labor force. By contrast, Tonawanda Powertrain has lost 3236 employees over this period, or 85.1% of their year-2000 workforce shown in Fig. 1. Toyota’s Kentucky plant was able to be as resilient as it was because it is the primary manufacturer of engines for the Camry Hybrid, which it has since 2006. The Camry hybrid saw its sales nearly double in just one year, before sales began to take a plunge as the global economic recession set in by the year 2008. Figure 8 shows the Camry hybrid’s yearly sales in the United States:

By the year 2020 the labor force of TMMK will be approximately 5901 hourly workers, down 699 workers from its 2010 work force of 6600, or a decrease of 10.6% compared to 15.4% from 2000-2010. This amount is significantly less than the forecast in job losses for Tonawanda Powertrain, pointing to the benefit from producing in-demand components such as the hybrid Camry engine; it is also conservative in the fact that it does not take into account future hybrid vehicles. Furthermore, even though jobs continue to be lost, the decrease in the rate of jobs being lost points to the stability that the hybrid engines may be able to bring to TPT. If TPT can retain jobs rather than lose them, it could allow the facility to continue to operate long enough to see the demand for hybrid engines increase to the point where it became necessary to hire new laborers for new manufacturing lines at the plant. Considering the increase in sales of the Chevrolet Volt since its debut, there is good reason to assume that GM has at last made one very beneficial decision for all of its facilities. If demand brought the Volt up to the sales numbers of the Toyota Prius, it would be an increase of 195% from the last known recorded sales for the Volt, of 1,703 total units sold as of April 2011 [33]. Considering such a large increase, it would be necessary to share the production across a number of different facilities, with the expectation that TPT’s reputation under GM would make it a prime candidate.

**BENEFITS TO WESTERN NEW YORK AND TO GM**

With an increase in labor force, the Town of Tonawanda would see a direct relationship between the number of people employed at the plant and amount of disposable income; with more people working, more money would be allowed to flow into the area’s local economy. With Tonawanda Powertrain being at one time the area’s largest single source of employment, a return to the type of economy caused by an upswing in the automotive plant would be a welcome change,
especially considering the unemployment rate in the Buffalo-Niagara Falls area where Tonawanda, NY is located, shown in Figure 9:

![Unemployment Rate in Buffalo-Niagara Falls Area: 2000-2010](image)

**Figure 9**: Unemployment Rate in Erie County from 2000-2010. Adapted from [25] using data taken at December of every year (trend line shown dashed).

The trend shows a general increase in the unemployment rate over the course of the decade, which accompanies the decrease in Tonawanda Powertrain’s workforce every year (Fig. 1). A welcome benefit for General Motors is that, as demonstrated in the Flint Michigan example, although the plant will increase its taxable assets due to the investment into new manufacturing equipment, no actual facilities need to be built.

This means GM can avoid a significant increase in City of Buffalo property taxes since it will not be expanding the actual size of the facility. Rather, the facility already in existence simply needs to be updated to produce a new kind of engine that it has never seen before. These additions require new jobs for man-power, for purchasing, for shipping, for setup, for maintenance, etc., all adding to the increased economic benefit to the area. Furthermore, new manufacturing stations, new machinery, new tools, new training, and other equipment would be added to the pre-existing operations in Tonawanda, but no new property taxes will need to be paid on top of what is already 3.1 million square feet of floor space [10]. This is especially beneficial for GM since, under the City of Buffalo, the Town of Tonawanda property is assessed on the basis of 100% of its value rather than 50% or 42% as seen in other towns and cities in the area [37]. This high percentage makes the Town of Tonawanda particularly costly for larger properties like Tonawanda Powertrain.

Taxes and bad decision making in Buffalo have created a long history of keeping new business from planting its seeds in the area, as well as scaring current business away. Most recently, billionaire and Buffalo Sabres co-owner Tom Golisano—who once brought business to the state, decided that it was time to move out [35-36]. As more and more business continues to avoid the area, the problem with industry such as GM’s Tonawanda Powertrain plant will occur in higher frequency. The only logical method of reversing what has been done over decades of poor political decision is to weigh the benefits and drawbacks of potential new business strategies such as the revival of plants like TPT.

**CONCLUSIONS AND RECOMMENDATIONS**

All economic indicators point to the viability of hybrid engines bringing the next wave of economic stability to the automobile industry. For a plant rooted in gasoline-only engines such as Tonawanda Powertrain, the transition to a hybrid line can occur only as quickly as the parent company—GM—can realize the harm in mass-producing something not wanted by the market. However, with proven to be one of the strongest and most efficient workforces under GM’s belt, it makes perfect sense economically for that transition to occur. Given that the benefits to GM’s sales could outweigh the potential losses in increased taxes, the Western New York region is wondering why that decision has yet to be made.

**REFERENCES**


ACKNOWLEDGEMENTS

To Dr. Jeanette Mitchell of the Economics Department at the Rochester Institute of Technology, who helped improve the statistical correlation between labor and sales data and the regression analyses. Dr. Mitchell introduced improved economic forecasting modeling and methods for use in this paper.
HORIZONTAL AXIS WIND TURBINE POWERTRAINS

Dylan Connole
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

Horizontal axis wind turbine powertrain systems are discussed, focusing on the powertrain presented in Variable Speed Wind Turbine with Radially Oriented Gear Drive by Baek et al. The drivetrain system is presented from the rotor blades, hub, torque tube, bearings assemblies, planetary gear set, and AC generator rotor shaft. The theory governing the system performance is also presented including the input power generated, torque and power transmission through the system, design consideration stresses, and efficiency. The theory is used to analyze an example horizontal wind turbine powertrain system. Background of the technology, market trends, future outlook, and recommendations are also discussed.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area Swept by Rotor Blades</td>
<td>(m²)</td>
</tr>
<tr>
<td>B</td>
<td>Number of features</td>
<td>(---)</td>
</tr>
<tr>
<td>C_p</td>
<td>Coefficient of Performance</td>
<td>(---)</td>
</tr>
<tr>
<td>K</td>
<td>Gear Ratio</td>
<td>(---)</td>
</tr>
<tr>
<td>L</td>
<td>Length of Spline</td>
<td>(m)</td>
</tr>
<tr>
<td>N</td>
<td>Number Gear Teeth</td>
<td>(---)</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
<td>(W)</td>
</tr>
<tr>
<td>n</td>
<td>Rotational Speed</td>
<td>(rev/min)</td>
</tr>
<tr>
<td>r</td>
<td>Radius from center</td>
<td>(m)</td>
</tr>
<tr>
<td>u</td>
<td>Wind Speed</td>
<td>(m/s)</td>
</tr>
<tr>
<td>w</td>
<td>Width of Spline</td>
<td>(m)</td>
</tr>
<tr>
<td>𝜏</td>
<td>Torque</td>
<td>(N∙m)</td>
</tr>
<tr>
<td>η</td>
<td>Efficiency</td>
<td>(---)</td>
</tr>
<tr>
<td>ρ</td>
<td>Density of Air</td>
<td>(kg/m³)</td>
</tr>
<tr>
<td>τ</td>
<td>Shear Stress</td>
<td>(N/m²)</td>
</tr>
<tr>
<td>ω</td>
<td>Angular Velocity</td>
<td>(rad/s)</td>
</tr>
</tbody>
</table>

Subscripts & Superscripts

ave Average
b Bolt
in Input to the System
max Maximum
o Outer radius
p-s Planet to Sun Gear Interaction
r-p Ring Gear to Planet Gear Interaction
r Ring Gear
s Sun Gear
sys System

BACKGROUND

The technology herein focuses on transmission of energy captured from wind at varying conditions by a through variable radially oriented gear powertrain system to an AC power generator. The primary topic is the transmission through the powertrain although related topics such as aspects of the wind turbine blades and power generator are also presented.

Wind turbines provide a method for capturing wind energy and through mechanical motion and convert it into energy. Although wind energy currently provides 187.9GW in the United States, it is still largely an untapped resource [1]. Taking into account land with moderate use, environmental restrictions, and area within 10 miles of transmission lines in the United States, the potential power at a 50m hub height is 734,073 MW [2]. This figure can be compared to the current US production capacity of 40,181 MW in 2010 [3]. This shows the ability to increase the US wind production capacity by over 1800% without installing any significant transmission lines. The states identified with the highest wind potential are in the Midwest states stretching from North Dakota to Texas [4]. If it is reasonable to assume that transmission lines are installed between major cities and generation plants then the low population density in most of these states leaves the conclusion that a low amount of the high potential area is currently within 10 miles of current transmission lines. If new lines were installed in these areas the potential for new capacity would increase drastically. The industry has reflected this opportunity by showing tremendous growth in recent years. The industry grew rapidly in 2007, 2008, and 2009 installing 5,258 MW, 8,366 MW, and 10,010 MW of wind power capacity respectively [3]. Global economic downturn impacted the wind industry as well shown by the installment of only 5,116 MW of new capacity installed in 2010; a reduction of nearly 50% from 2009 [3]. Despite this reduction, the industry is showing signs of improvement in that 3,195 MW of the installed capacity from 2010 came in the fourth quarter and in the first quarter of 2011 5,600 MW of wind power capacity respectively [3]. With limited fossil fuels available wind energy is becoming a significantly larger part of the global energy market.
As the industry grows and strives to produce ever larger turbines to maximize output problems are encountered such as supporting a long nacelle. The nacelle length in traditional turbines is driven by the powertrain system which has a linear component layout that can lead to problems with inefficient power transmission, dynamic loads conditions, unbalanced loads, alignment errors, and higher costs [5]. Using a radial gear powertrain system can increase efficiency through use of planetary gears and reduce size though concentric cylinders. This compact and more efficient system leads to fewer problems, less maintenance work, easier construction of turbines, cost savings through reduction of materials, and greater output.

Basic wind turbine technology has been employed for hundreds of years; however, the technology is still being researched and improved upon. The industry has now converged to the standard large scale single tower, three blade design and most of the efforts are now to maximize the efficiency and power generation. Improvements have been made to the turbine blades to maximize the wind energy, but more recent efforts are to increase the efficiency of the powertrain system through new designs such as radial designs and magnetic gearing. Magnetic gearing offers several benefits such as reduced wear, eliminating the need for lubricant, reduced maintenance costs, and automatic overload prevention as the gears will slip harmlessly when over torque and reengages when the torque falls below the maximum torque [6].

**DESCRIPTION OF THE TECHNOLOGY**

The following description is adapted from Baek et al. [5]. As illustrated in Figures 1 and 2, in this horizontal axis wind turbine system the rotor blades 50 connect to individual blade pitch change mechanisms 52 which are mounted on the central hub assembly 54. The hub is attached to the outer cylindrical member 22 of the powertrain. The outer cylindrical member 22 is supported by a pair of large annular bearing assemblies 17 and 18, comprising tapered roller bearings. Member 22 in turn is connected to torque tube 49 which has an internal ring gear 48 that engages planet pinion gears 46. Planet pinion gears 46 are connected by shafts to drive planet gears 43. The planet gears 43 mesh with the sun pinion gear 42. The sun pinion gear is formed on the end of the high speed shaft 62 which is attached to the generator shaft 60 by a mechanical coupling 64. This mechanical coupling 64 is preferably done a means, such as being pinned, that allows a small amount of motion off the axis of shaft 62 to prevent bending and problems at the sun and planet gear interface. It could also have internal splines and be press fitted if necessary. Coupling 64 allows the electric alternating current generator 58 and the shaft 60, which is the rotor shaft coming from the generator and entering through the support frame 56, to be removed from the system in the event of a failure. The AC generator 58 is mounted on the support frame 56 which is then supported by flange 24. The generator shaft 60 also extends out the opposite direction where the end is attached using another mechanical coupling 66 to another shaft extension 68 for a breaking system.

![Figure 1. A partial cross-sectional view of a radially oriented gear drive assembly used in the presented turbine model. Adapted from [5].](image1)

![Figure 2. A simplified cross sectional view of a wind the radially oriented wind turbine powertrain. Adapted from [5].](image2)

Figure 3 shows an alternative embodiment of this powertrain system that reduces the design envelope further. The technology remains the same, but for this embodiment the AC generator 58 is mounted in the center of the hollow region of the system to reduce the length of the system. It is attached concentrically to the inner cylindrical hollow member 21. The only significant design difference with this design is that...
shaft 62 is attached to the opposite side of the sun pinion gear 42 to extend toward the AC generator 58.

Figure 2. A cross sectional view of the alternative embodiment of the radially oriented wind turbine powertrain in Figure 2. Adapted from [5].

LITERATURE REVIEW

The following description is adapted from Baek et al. [5]. Early horizontal axis wind turbines using aerodynamic lift were introduced as early as the 12th century, but in 1888 the Brush wind turbine produced 12kW of usable DC power [7]. While much of the early turbine technology declined with introduction of rural grid connections, Palmer Putnam’s Grandpa’s knob machine, a 1.25MW rated turbine with full-span pitch control, active yaw drive, fixed rpm, and a two bladed flapping rotor, managed to succeed [7]. Variable speed grid-tied turbines became viable in the 1970s as machines such as the Windworks 8kW turbine, which used a diode bridge to rectify the output from a permanent magnet generator, began use of modern silicon-controlled rectifiers [7].

Individual companies are making contributions to developing this technology through private research and development. Vestas, a leader in wind energy, announced a new 7.0MW turbine to be installed in offshore locations [8]. Although direct drive and geared solutions were both considered, the V164-7.0MW will use a medium speed drive train solution to keep costs as low as possible [8]. StatoilHydro installed a new deep water turbine, Hywind, which implements a Siemens SWT-2.3-82 turbine on a floating spar [9]. The SWT-2.3-82 uses a custom 3 stage helical planetary gear set mounted on the nacelle using rubber bushings [10].

Magnetic gearing systems which avoid many problems of a conventional powertrain have been patented and are being implemented in various applications. Patten application 0042965A1 describes several embodiments of magnetic powertrains which use a variable magnetic gear stage and a pseudo direct drive to replace the direct drive or mechanical gearing [6].

Companies in wind turbine manufacturing, gear manufacturing, and bearing manufacturing have encountered problems with gearbox reliability, namely that gearboxes have not reached their designed twenty year life goal, in part due to proprietary ownership of the system components [11]. The National Renewable Energy Laboratory (NREL) has taken measures to research these issues by including a variety of stakeholders and analyzing a generic turbine gearbox assembly by implementing a three part approach: drivetrain analysis and modeling, full scale dynamometer testing, and field testing [11]. This approach aims to investigate many factors that could be affecting the gearbox life deficiency including that the transfer of loads from the shaft and mounting reactions is in a nonlinear or unpredicted manner, the possibility that critical design-load cases were not accounted for, and that some gearbox components, especially bearings, are not uniformly specified to deliver the required reliability [11].

OPERATION OF THE TECHNOLOGY

Wind flows over the rotor blades 50 creating distributed lift and drag forces along the blades. The drag force is parallel to the axis of rotation and does not contribute to the input to the powertrain system, but creates bending in the rotor blades 50. The aerodynamic design of rotor blades aims to reduce the drag that is created in order to minimize stresses on the turbine components, especially the rotor blades 50 and the hub assembly 54. The lift force is perpendicular to the axis of rotation and is the component that is captured to produce torque in the system and generate power. The force on the blades is transmitted by rigid connections through the rotor blade 50, the blade pitch change mechanism 52, and the hub assembly 54, to the outer member 22 where the lift force on the rotor blades 50 creates a torque about the axis of rotation.

The outer member 22 rotates clockwise on annular bearing assemblies 17 and 18 attached to the fixed inner member 21 as a result of the torque from the rotor blades 50. The annular bearing assemblies 18 and 18 must be large to have the necessary durability to maintain proper performance and avoid failure in fluctuating wind conditions. They are preferred to be consisting of of tapered roller bearings because of their
application to the loading conditions. The torque is then transferred through a bolted connection to the large diameter torque tube 49. The entire torque in the system is transferred through this bolted connection which will put significant shear stress on the bolts. Both the size of the bolts and number of bolts will need to be large to endure the shear stress without failure.

The torque tube 49 has an internal ring gear 48 which engages the teeth of the three planet pinion gears 46 and causes them to rotate. The planet pinion gears 46 are able to rotate about each of their own central axis, and do so in the same clockwise direction as the torque tube, but as a set do not rotate about the axis of the planetary gear assembly. The torque from the ring gear 48 is transmitted to the planet pinion gears 46 reducing the torque but increasing the angular velocity. The planet pinion gears 46 mesh with the sun pinion gear 42 rotating it the opposite direction than the torque tube 49. The second gear interaction reduces the torque and increases the angular velocity again.

The sun pinion gear 42 is formed on the end of the high speed shaft 62 which is attached by coupling 64 to rotor shaft 60 of the AC generator 58. The coupling interaction must withstand high rotational velocity wear and any vibration in the system.

THEORY OF THE TECHNOLOGY

The rotor moves at rotational speed, \( n \), depending on the size and model of the turbine. This rotational speed can be used to determine the angular velocity, \( \omega \), by converting to the correct units as shown by Eq. (1).

\[
\omega_{in} = \frac{2\pi n}{60} \quad (1)
\]

Wind turbine blades are able to generate power guided by Eq. (2), adapted from Johnson’s Wind Energy Systems [12].

\[
P_m = C_p \left( \frac{1}{2} \rho A u^3 \right) \quad (2)
\]

Where \( P_m \) is mechanical power, \( \rho \) is the density of air, \( A \) is the swept area of the turbine, and \( u \) is the speed of the wind. \( C_p \) is the coefficient of performance which is the percent of wind power that is actually extracted by the turbine and varies with wind speed, rotational speed of the turbine, and turbine blade parameters. Torque is calculated as the mechanical power input over the rotational speed as shown by Eq. (3).

\[
T = \frac{P}{\omega} \quad (3)
\]

Here Eq. (3) can be used to calculate the torque input of the turbine based on known or estimated parameters.

The annular bearing assemblies are relied upon to withstand axial and radial loading in transient heavy loading conditions caused by strong gusting winds. Tapered roller bearings were recommended based on these loading conditions and this bearing type’s ability to perform under the conditions. Spherical roller bearings are also commonly used on wind turbine bearing assemblies because they allow for small misalignments, absorption of radial forces such as hub weight, and absorption of axial forces from dynamic loading conditions. Any bearings used for this application must resist the heavy loading while transmitting high torque generated without failure.

The Torque generated by the rotation of the outer member is transferred to the torque tube by a bolted connection. Here the bolted connection is subjected to the full torque of the wind input. Combining the knowledge that torque is the product of force and distance and that shear is force over an area, the expression, Eq. (4), for the shear stress in each bolt is reached.

\[
\tau_b = \frac{T}{r \pi r_b^2 B} \quad (4)
\]

This calculation is conservative because it transfers all of the torque through the shear in the bolts assuming that there is no friction on the connection. This stress is then used to select the appropriate type of fastener and the number needed.

Chris Layer’s presentation on planetary gear trains provides the general equation, Eq. (5), for a planetary gear system.

\[
\omega_s + K \omega_r = (K + 1) \omega_i \quad (5)
\]

K is called the gear ratio and is shown in Eq. (6) as the ratio of teeth in the ring gear to teeth in the sun gear.

\[
K = \frac{N_r}{N_s} \quad (6)
\]

In this planetary gear design the carrier is fixed. Making this simplification to eliminate the carrier rotation term and re-ordering the equation to solve for the rotation of the sun pinion gear Eq. (7) is reached.

\[
\omega_s = -K \omega_r \quad (7)
\]

The torque transmitted through the system is subjected to the inverse relationship as shown in Eq. (8).

\[
T_s = -\frac{1}{K} T_r \quad (8)
\]

The negative sign only implies that the torque is working in the opposite direction after the planetary gear. In Eq. 5-7 the gear teeth ratios are used; however, this ratio is analogous to the ratio of the radii of the gears. Substituting Eq. (6) and (7) into Eq. (1) shows that the theoretical power before and after the planetary gear set is the same. Reality dictates that this is not a perfect connection due to non-conservative forces, mainly friction, acting upon the gear teeth. The actual efficiency of the planetary gear
Using a turbine with a 50m rotor blade, a reasonable value for almost all large scale wind turbines. Using Eq. (1) with this value to determine the angular velocity gives Eq. (13),

\[ \omega_{in} = \frac{2\pi \times 10}{60} = 1.047 \text{ rad/s} \]  (13)

The torque is needed to calculate stresses so using Eq. (3) with the values calculated yields a torque of 1.355MNm according to Eq. (15).

\[ T = 1.419 \times 10^6 \times 1.047 = 1.355 \text{ MNm} \]  (15)

The sun pinion gear is directly linked to so the torque and angular velocity of the ring gear are the same as the input so Eq. (7) and (8) can be used, shown by Eq. (16) and (17), to calculate the values for the high speed shaft which drives the output. The value for K is assumed knowing it is in the possible range and an increase in the angular velocity is desired.

\[ \omega_s = -100 \times 1.047 = -104.7 \text{ rad/s} \]  (16)

\[ T_s = -\frac{1}{100} \times 1.355 \times 10^6 = -13.55 \text{ kNm} \]  (17)

The sun pinion gear is directly linked to so the torque and angular velocity of the output are the same as the sun.

The efficiency, using .9875 mesh efficiency presented by Chris Layer, is calculated by Eq. (18).

\[ \eta_{sys} = \frac{1 + 100 \times .9875 \times .9875}{100 + 1} = .9754 \]  (18)

This combination of large gear ratio and high system efficiency is the reason planetary gear systems are used in wind turbines. This leads to a power of 1.384 MW going to the AC generator. Additional losses in the motor will reduce the total output of the turbine, but losses beyond the powertrain system are not in the scope of this analysis.
DISCUSSION

Along with the increasing focus on renewable energy, the wind power industry receiving increased attention as the countries try to reduce fossil fuel use and gain energy independence. As a result it is a rapidly growing industry that appears to only increase in the relative future as discussed earlier. Supporting this are the policies implemented, especially in the US and Europe. In the US, 43 states plus Washington D.C. have net metering policies while an additional three have voluntary utility programs [16]. Also 29 states and Washington D.C. have Renewable Portfolio Standard (RPS) laws to facilitate the use of renewable energy [16]. The European Union has gone beyond state and federal laws to set an aggressive goal of 20% of all energy coming from renewables by 2020. With most western countries adopting some sort of incentive policies for renewable energy, the future of wind power is certainly growth.

While some of the technology relating to wind turbines, such as tower and blade design, have converged onto a standard, the specific technology of horizontal axis wind turbine powertrains has become one of the areas that has significant variation and remains open to a new designs and technical improvements. Currently the standard is to use a geared powertrain; however, many other systems are being investigated. Direct drive systems are present in turbines but do not make up a significant market share and have problems arising from the size of the generator needed [17]. Hybrid drives have also been introduced that strive to combine geared and direct drives to have a balanced system that is less susceptible to problems [17]. Other innovative systems being researched and tested are based on hydraulic drives which are claimed to greatly reduce weight from based on their higher power density and hydrodynamic torque converters which ensure a synchronous generator can be used [17].

A considerable portion of the recent improvement relating to powertrains has come from improvements in manufacturing technology. This improvement was due new technologies such as CNC and CAD which removed significant human error from the manufacturing process. Although manufacturing technology appears to be slowing, the options that are now possible have certainly not been fully explored.

CONCLUSIONS AND RECOMMENDATIONS

Wind turbines have three primary areas that will lead to significant development: turbine size, installation location, and powertrain design. Due to new materials technology and manufacturing abilities the most prominent trend in wind turbine technology is the increasing size because it is the design aspect with the most impact on power production. Turbines planned to be built are continuously larger and with the larger turbines comes new design challenges in the production of large components, developing low cost drive trains to transfer high torque movement to high speed output, and heat removal.

Installation location has a surprising correlation to demands of the powertrain system. The demands change significantly based on location if the turbine and some of the highest wind potential locations have harsh conditions. In desert locations extra care must be taken to avoid dust in the system while offshore applications must take extra care to avoid rusting and salt degradation. Additionally striving to reduce social impact, based on the public desire to not see or hear turbines, and maximize wind speeds deepwater turbines have become a key area of development. Deepwater turbines provide a new set of challenges for capturing maximum wind energy with a dynamic foundation.

The variety of powertrain designs considered at present shows that there is opportunity for improvement. As presented by NREL, the analysis and design of turbine powertrain systems has not been perfected, especially for turbine bearings. Cooperation between all parties or vertical expansion would greatly improve ability to design and analyze higher quality products. The technological improvements of the past decades will also lead to experimenting with new designs previously discussed that could lead to breakthroughs for wind power.

Although opportunity for growth has been provided by materials and manufacturing capabilities, the driving force behind wind energy is the limited fossil fuels and the growing environmental consciousness of western culture. However, some people still are objected to wind turbines even if they will not say it outright, but they are opposed seeing any wind turbines. Engineers must work through a variety of social constraints set by the public about what turbines should look like, where they should be, and how silent they must be and still create an efficient turbine. The reality of this is that the standard turbine tower is less efficient than a lattice tower, there is very little land to build where nobody can see the turbines, and turbines take up much more space than coal plants. Despite these people, the public still supports wind power and with their support the wind sector will be pushed to continue development of the technology.
For a company to excel in the wind turbine industry the company must pursue three activities. First is to expand vertically, bringing the manufacturing process under one roof to reduce cost and unify the design process. Second is to develop a practical solution to build large scale deepwater wind farms. Finally, the company must develop a powertrain system that is cost effective to produce and has a sufficient part life.

REFERENCES

FLYWHEEL KINETIC ENERGY STORAGE

Matt DeRosa
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
Flywheels have a history of being used in applications to smooth out energy transfer and store energy. The development of flywheels into energy storage devices has grown recently and is an emerging technology. The idea is that the flywheel will serve as a sort of rechargeable kinetic battery, being able to charge and discharge depending on supply and demand. There are advantages of using a kinetic energy source over other battery technologies such as chemical. There is a vast range of applications for the technology. As the technology has developed it is being explored to impact the electrical grid and even the auto industry. It is a leading technology in the drive for a more energy efficient future that doesn’t depend on fossil fuels.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Kinetic Energy</td>
<td>(Nm)</td>
</tr>
<tr>
<td>P</td>
<td>Potential Energy</td>
<td>(Nm)</td>
</tr>
<tr>
<td>g</td>
<td>Gravity</td>
<td>(N/s^2)</td>
</tr>
<tr>
<td>h</td>
<td>Height</td>
<td>m</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td>kg</td>
</tr>
<tr>
<td>K</td>
<td>Shape factor</td>
<td>dimensionless</td>
</tr>
<tr>
<td>V</td>
<td>Velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>I</td>
<td>Inertia</td>
<td>kg*m^2</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
<td>N</td>
</tr>
<tr>
<td>B</td>
<td>Magnetic Field</td>
<td>Kg/(C*s)</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
<td>m</td>
</tr>
<tr>
<td>I_m</td>
<td>Current</td>
<td>amps</td>
</tr>
<tr>
<td>K_t</td>
<td>Motor Constant</td>
<td></td>
</tr>
<tr>
<td>T_m</td>
<td>Motor Torque</td>
<td>Nm</td>
</tr>
<tr>
<td>E_m</td>
<td>Motor Voltage</td>
<td>Volts</td>
</tr>
<tr>
<td>K_v</td>
<td>Motor Constant</td>
<td></td>
</tr>
</tbody>
</table>

Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ω</td>
<td>Rotational Speed</td>
<td>(rad/s)</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
<td>(N-m)</td>
</tr>
<tr>
<td>σ</td>
<td>Stress</td>
<td>N/m^2</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>Kg/m^2</td>
</tr>
</tbody>
</table>

BACKGROUND
With the expansion of renewable energies and their integration into the grid the demand for energy storage has grown. An issue with natural resources of energy is that they are intermittent. The wind that supplies the source for a wind turbine can’t always be expected to blow at a constant rate. The output of a renewable resource power plant does not always correspond with the demand on the grid. Technologies that can capture the extra energy when it is produced and supply the captured energy to the grid when there is a shortage and being developed and implemented in parallel with renewable energy power plants. One of these technologies is Flywheel energy storage. Beacon Power constructed a 20 MW flywheel energy plant outside Stephentown, NY recently and another plant is planned for construction near Chicago.

The technology doesn’t have to have a large scale application as in a power plant setting. Industry uses battery technology to balance the industry’s own frequency regulation needs. It works the same as it does as an energy power plant. An example of this being used would be in the startup of machinery and the shutdown of machinery. When the switch is flipped immediately following there is either excess energy or a shortage.

As well as having applications in the electric grid there are many other smaller scale applications. They have been utilized in many stop and go applications where quick charge and discharge cycles are common. Delivery trucks are a good example where kinetic batteries could be utilized to save fuel economy. The auto industry is making strides in becoming more fuel efficient as government regulations tighten and the cost of fuel increases. Not only has the technology been shown to have fuel economy benefits but also has applications in performance cars. Formula 1 banned the technology briefly but has recently lifted the ban. Porsche used flywheel energy storage to boost their car in situations.

Flywheel energy storage systems are an emerging technology being developed in a very competitive industry. The technology is competing against other more widely accepted technologies such as chemical batteries, compressed air and pumped hydro.

DESCRIPTION OF THE TECHNOLOGY
The technology has come a long way from the first flywheel energy storage devices. The kinetic energy storage device is a combination of electrical
and mechanical components. Figure 1 shows a design of a flywheel energy storage device.

![Figure 1. Illustration of a modern flywheel energy storage device. Adapted from [1].](image)

At the core of the device is the flywheel. The flywheel of the device shown is made of carbon fiber. Older flywheels were designed as massive steel discs; recently flywheels have been designed of higher strength materials and smaller so they can spin faster. The strength of the flywheel dictates how fast the system can spin and how much energy it can store [2]. The equation for this is

\[ E_m = K \sigma_{\text{max}} \rho \]  

(1)

The flywheel connects to the rotor. The rotor is either an electromagnet or a permanent magnet. The issue with permanent magnets is demagnetization over time. The rotor is part of a motor/generator.

Also part of the motor generator is the stator. The stator interacts with the rotor to carry a current either to charge or discharge the kinetic energy storage device. The stator is constructed of wound copper wire.

Magnetic bearings at the top and bottom of the shaft connected to the rotor. Ball bearings were used before but introduced friction and heat. The introduction of magnetic bearings has made the entire system much more efficient [3].

Axial magnets are also used to levitate the shaft and rotor [4].

Another system in some flywheel energy storage units is a vacuum chamber located between the flywheel and the housing. If sealed properly a pump is not needed to maintain the vacuum but in some cases a pump is necessary in order to keep the flywheel rotating in a near drag less environment [1].

The final main subsystem is the housing. The housing encloses the device from the environment and protects from the event that the max stress of the flywheel is exceeding causing a catastrophic failure.

**LITERATURE REVIEW**

The technology is being developed by many separate companies to be used in a wide range of applications. There is also a great deal of work being done in the academic community. The main drivers for this technology today are the integration of renewable resources in the construction of a smarter electrical grid. The most current information found on the topic is on strategies to implement energy storage into the grid. There are many papers found in online data bases that show the advantages of pairing flywheel energy storage with renewable energy power plants, such as wind power.

There are many studies published displaying the viability of flywheel energy storage in parallel with the electric grid. Matlab simulations show the outputs and benefits of flywheel energy storage technology. *Coordinated Multi-Objective Control of Regulating Resources in Multi-Area Power Systems with Large Penetration of Wind Power Generation* by Preben Nyeng, Bo Yang, Jian Ma, John H. Pease, David Hawkins, and Glyde Loutan looks at the flywheel technology and pumped hydro paired with wind power generation. They simulate the behavior of the system using matlab. It shows that the flywheel technology is much more effective then pumped hydro because of its ability to have a fast response time. The paper also talks about how flywheel technology paired with pumped hydro would lessen the wear and tear on pumped hydro components [5].

*Grid-Scale Frequency Regulation Using Flywheels* by Matthew L. Lazarewicz and Todd Ryan explains about the projects in NY and other markets. Significant ground has been made by Beacon Power constructing a plant outside Stephentown NY and another to begin construction soon in outside of Chicago, IL. [4]
flywheel energy storage technology on the electric grid. From reference[4]

The technology is compared to similar technologies. Comparisons are done between the kinetic energy storage with other competing technologies. Some of these other technologies are pumped hydro, compressed air and chemical battery. The benefits of kinetic energy storage over chemical batteries are found on most kinetic energy storage device supplier’s websites. One supplier that posts a comparison is Power-Thru(http://www.power-thru.com/22.html) [1].

Fuel Saving Flywheel Technology for Rubber Tired Gantry Cranes in World Ports is written about Vycon flywheel energy technology in saving fuel for ports. It was found that with flywheel technology there was a 38% reduction in fuel use across the port in crane operations [6].

OPERATION OF THE TECHNOLOGY

The kinetic energy storage device isn’t a very complicated device. It involves converting energy from electrical to kinetic in the charge process and then reversing the process to discharge. It has only a few moving parts.

During the charge cycle current is passed through the stator. The stator is comprised of wound copper wires. The stator is around the outside of either an electromagnet or permanent magnet rotor. The resulting magnetic field intercepts the current. When the current is passed through the magnetic field a force is created on the rotor. The force then creates a resulting torque that spins the rotor. The rotor can be part of the flywheel or there’s a physical connection from the rotor to another flywheel. As the rotor and flywheel increase the rotational velocity the Kinetic energy of the system increases. The energy that was in the current is now stored as kinetic energy in the flywheel. As the rotor spins a back electromagnetic force (back emf) is created which is a voltage in the reverse direction of the supply voltage.

THEORY OF THE TECHNOLOGY

Energy is introduced to the system by the current through the stator [7]. The force exerted on the rotor can be described by the equation

\[ F = BLI \sin(A) \]  (2)

Where A is the angle between the magnetic field and the current. This force is applied to the rotor. The force is applied to the radius of the rotor so

\[ T_m = F \times r \]  (3)

The torque induced on the rotor from the current passing through the stator can also be represented by the equation

\[ T_m = K_t * I_m \]  (4)

\[ K_t \] is a motor constant. The current is limited by the back-emf of the motor/generator. The back-emf is a voltage in the reverse direction of the supply voltage.

\[ E_m = K_m * I_m \]  (5)

\[ K_t = K_m \]  (6)

The equation for the basic electrical circuit is involves a resistor, current, a source voltage and the back-emf of the motor. The motor isn’t the only part that draws power. There are also electromagnets and vacuum pumps in some cases.

\[ V_{source} = I_m * R + E_m \]  (7)

\[ V_{source} = I_m * R + K_m * I_m \]  (8)

The energy of the system can be evaluated by the energy equation for rotational energy. Through position and velocity sensors the rotational velocity is known. The inertia of the spinning mass is known by the design.

\[ T = \frac{1}{2} I \omega^2 \]  (9)

The kinetic energy of the system in modern flywheel energy storage systems can store energy for an hour effectively only losing .1% of the charge. Loses are kept to a minimum as long as the flywheel is kept in a vacuum to cut down on drag, friction is kept low by magnetic bearing and heat is kept low.
In a system such as a crane, energy is converted from a diesel generator to a height potential energy when the crane is lifted. When the crane is lowered, a motor is turned spinning a flywheel. That potential energy is represented by equation

\[ PE = mgh \]  

(10)

The potential energy is converted into kinetic energy:

\[ PE = T - \text{losses} \]  

(11)

Potential energy doesn’t have to be the only source for the flywheel. In the case of regenerative braking, rotational energy is being converted into kinetic energy. Just the location moves from the wheels to a flywheel.

**DISCUSSION**

Flywheel energy storage technology and technologies like it will be essential as populations grow and renewable technologies continue to replace fossil fuels. It will be needed in small and large scale applications. In applications like recovering energy for a crane on the harbor or regulating the electric grids frequency energy storage is going to grow in demand.

There are several reasons why energy storage and its integration into the electric grid have been slow in taking off. Flywheel energy technology has just started to be developed and integrated into the grid. One place it’s used is on Navy Air Carriers. To launch planes the plane needs to be accelerated to 200 mph in a few seconds. To release that amount of energy that quickly the navy uses flywheel technology. Relative to the amount of renewable energy projects underway the energy storage projects are small and few. Renewable energy plants are much more appealing to have government support than energy storage. One reason for this is that natural gas that is used to power turbines for frequency regulations remains low in cost. There also is no carbon tax on dirty turbines for frequency regulation. The cost to build a flywheel plant is large [8]. The plant built in NY outside of Stephentown cost $43 million.

85% charge and discharge efficiency is very good when compared to other technologies.

**CONCLUSIONS AND RECOMMENDATIONS**

With the advancement of magnetic bearings, flywheel energy storage technology is very promising in complementing renewable energy technologies. Beacon Powers first generation flywheel energy storage devices stored power for only 15 minutes. Now on their fifth generation storage time exceeds an hour. This is significant improvement and makes the technology all the more viable in the market. Some of the improvements can be accredited to the improvements in magnet technology as the flywheel is levitated by magnets and the bearings are also magnetic. In flywheel devices that require a vacuum pump, the pump must attribute to some of the loses in the length of charge.

Flywheel energy storage seems favorable to other technologies it is competing against. It doesn’t involve occupying large amounts of the water supply that pumped hydro demands. The footprint is small as well. There aren’t toxic chemicals to deal with either. The maintenance by many of the company websites is only required every six years with the lifetime around 20 years [1].

Chemical reactions are hard to depend on for power. There are many different factors that go into the optimization of the reaction. The gasoline engine is getting more efficient now as it has become possible to optimize the reaction process during combustion. To achieve this involves many other working parts that all consume energy in order to gain a little more back in return. The flywheel requires a pump to create a vacuum and electricity to power electromagnets. There aren’t many parasitic losses involved. This is in part due to the simplicity of the design of flywheel energy storage. Ideally energy storage wouldn’t be necessary. The source in that case would have to be instantaneous in order to regulate frequency. Since there is no such present source energy storage seems necessary.
There is also opportunity for businesses and industry to utilize flywheel technology to make savings. Flywheels can be used in applications such as cranes and buses to reduce fuel consumption and emissions. It also can be used to provide undisruptible power. Can be used in times to prevent a power outage or regulate frequency when heavy machinery is turned off.

It seems necessary that flywheel technology develops alongside the renewable energies in the United States. There is plenty of opportunity to incorporate the technology.

References


ACKNOWLEDGMENTS

Rochester Institute of Technology for Access to library and database.
THEORY AND OPERATION OF AUTOMOTIVE PEM FUEL CELL POWERTRAINS

Matthew L. Garofalo
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

Fuel cell vehicles (FCVs) with proton exchange membrane fuel cell (PEMFC) power plants, or fuel cell stacks, have substantial potential to become viable replacements for the internal combustion engines (ICEs) that power today’s conventional automobiles. Rising oil prices and increased carbon dioxide emissions from (ICE) vehicles into the Earth’s atmosphere have allowed for the auto industry to extensively seek out an alternative to this nonrenewable fuel burning and atmosphere polluting engine. The emerging sustainable technology of FCVs with PEMFC power plants boast certain favorable characteristics such as zero emissions, the use of a renewable fuel, high operating efficiencies, and high power density [1]. However the fuel cell power plant is not the only unique aspect of a FCV, the entire powertrain is substantially different than the conventional systems that are seen in most automobiles today and offer many more degrees of freedom with respect to their design and placement within the vehicle chassis [2].

This paper offers a background of fuel cell powertrains (FCPs) and why they are important in today’s automotive engineering community. It compares and contrasts conventional vehicle powertrain layouts to FCV powertrains as well as provides detailed descriptions of the system of different electrical and mechanical components that make up FCV powertrains. The paper’s exhaustive literature review provides a focus on the innovations made in the design of the fuel cell powertrain of the Honda FCX Clarity fuel cell hybrid vehicle, one of the most successful FCVs ever designed and is currently available for lease to the public in certain areas of the United States. The literature review showcases the many innovations of this unique vehicle and its powertrain components such as the electric drive unit and V Flow fuel cell stack and the gains made with respect to packaging the powertrain within the vehicle as well as the improved efficiencies obtained as a result. The operation of the typical FCP components such as the fuel cell stack, electric motor, gearbox, battery, DC/DC converter, inverter, and regenerative braking system all are described as well as how they all work together to form a complete system. This includes both the energy flow paths and energy conversion processes that occur throughout the powertrain as well as the flow paths of the water, hydrogen, and oxygen in the fuel cell stack. The theory of what factors play a role in affecting the performance of a fuel cell is provided in great detail. The various efficiencies with respect to the fuel cell and electric motor and the factors that affect them are reviewed as well. Finally a discussion is provided along with a conclusions section. In this section it was concluded that this novel type of powertrain has the potential to improve and essentially redesign the automobile as we know it as well as push the boundaries of engineering like never before. This paper showcases both the theory and operation of this interesting powertrain and provides much insight towards why these powertrains are an important aspect of not only modern powertrain design and innovations, but also vehicle chassis and body design as well.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Geometric Electrode Area</td>
<td>m²</td>
</tr>
<tr>
<td>E</td>
<td>Open Circuit Voltage</td>
<td>V</td>
</tr>
<tr>
<td>I</td>
<td>Electric Current</td>
<td>A</td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
<td>Wb/A</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
<td>W</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
<td>N∙m</td>
</tr>
<tr>
<td>V</td>
<td>Voltage</td>
<td>V</td>
</tr>
<tr>
<td>g</td>
<td>Gibbs Free Energy</td>
<td>J/mol</td>
</tr>
<tr>
<td>h</td>
<td>Enthalpy of Formation</td>
<td>J/mol</td>
</tr>
<tr>
<td>j</td>
<td>Current Density</td>
<td>A/cm²</td>
</tr>
<tr>
<td>p</td>
<td>Poles</td>
<td>(none)</td>
</tr>
</tbody>
</table>

Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε</td>
<td>Efficiency</td>
<td>(none)</td>
</tr>
<tr>
<td>λ</td>
<td>Stoichiometric Ratio</td>
<td>(none)</td>
</tr>
<tr>
<td>φ</td>
<td>Magnetic Flux</td>
<td>Wb</td>
</tr>
<tr>
<td>ω</td>
<td>Rotational Speed</td>
<td>rad/s</td>
</tr>
</tbody>
</table>
BACKGROUND

Rising oil prices and increased carbon dioxide emissions from ICE vehicles into the Earth’s atmosphere have allowed for the auto industry to extensively seek out an alternative to this nonrenewable fuel burning and atmosphere polluting engine. The emerging sustainable technology of FCVs with PEMFC power plants have substantial potential to be viable replacements for ICEs due to certain favorable characteristics such as zero emissions, renewable fuel, high efficiency, and high power density [1]. Major auto companies like Honda have been working diligently toward a fuel cell vehicle to add to the fleet of vehicles they have to offer. In 2002, Honda produced the first FCV certified by the United StatesEnvironmental Protection Agency (US EPA) called the FCX[2]. General Motors (GM) has successfully implemented the world’s largest fuel cell vehicle market test called “Project Driveway” which entailed a three-city wide test of their 4th generation FCP packaged in a Chevrolet Equinox platform [3]. Toyota has also been working on a FCV powertrain since 1992 and has adopted it into the Toyota Highlander platform. In 2002, Toyota became the world’s first automobile manufacturer to offer a fuel cell vehicle for lease [4]. It is quite clear that fuel cell technology is of great interest to top auto manufacturers and that these novel powerplants have great potential to power cars in the future. With this new powerplant development comes the development of new powertrains specifically designed for harnessing the energy put out by the fuel cell stack and efficiently transferring it to the vehicle’s wheels. Honda’s FCX Clarity is a brand new model with a new chassis and vehicle infrastructure designed specifically around a FCPrather than an ICE model adapted to a FCPlike GM and Toyota have done. In turn, it showcases all the advantages gained through fuel cell technology [2]. Some of these advantages include the various ways that the efficient and compact FCP components can be easily distributed throughout the vehicle platform thus allowing for a higher degree of freedom in the layout design [2]. This allows for the maximization of cabin space as well as the optimization of vehicle weight distribution and center of gravity [2]. The FCX Clarity for instance, achieved the cabin space of a large class body in a medium class body by employing these new flexible design paths and increased options for vehicle optimization [2]. GM’s Chevrolet Sequel concept achieved an “ideal” 50:50 weight distribution through their fuel cell enabled “skateboard” chassis architecture [5]. Compact front wheel drive (FWD) electric motors that receive the electric power from the fuel cell stack offer the ability to shorten the nose of FCVs and in turn offer a spacious cabin [2]. These motors emit less vibration and noise than an ICE and thus allow for a smootherand quieter ride [2]. The torque output of the electric motor is continuous and does not require a gear shift [2]. This aspect also allows for rapid acceleration pickup and smooth acceleration across the entire range of vehicle operation [2]. Finally, there are less moving parts in a fuel cell powertrain and, in turn, they require less maintenance and lubrication [2]. The efficiency at which energy is converted in an automotive powertrain is becoming more and more important due to the recent push to produce more fuel efficient and sustainable automobiles. There is great potential to improve the efficiency of automotive powertrains above the current conventional internal combustion engine level through the use of PEMFC technology as well [5]. This potential exists in the flexibility of the performance level of the energy conversion and storage devices. This coupled with different modes of operation for different driving conditions immensely improve the overall efficiency of the vehicle powertrain [6]. The lower number of moving parts decreases the running resistance and in turn also increases the powertrain’s efficiency [2]. The FCX Clarity achieves a 60% operating energy efficiency, a number that is more than three times greater than a compact gasoline vehicle and more than two times greater than that of a compact hybrid vehicle [2]. The fuel economy of the FCX Clarity is also higher at 2.1 times greater than a compact gasoline engine vehicle and 1.4 times greater than a compact hybrid vehicle [2].

DESCRIPTION OF THE TECHNOLOGY

A typical FCP consists of four main components including the fuel cell stack, battery assist, electric motor, and gearbox. This type of battery assisted powertrains called a fuel cell hybrid powertrain [7]. The fuel cell stack is where the hydrogen and oxygen react to produce DC electric current. The electricity can be stored in the battery for later discharge, inverted to power an AC electric motor, or converted to power a DC electric motor. These electric motors are, in turn, coupled to the vehicle’s differential which provides the desired gear reduction in order to power the vehicle’s wheels. The gearbox can be in the front or rear of the vehicle but most FCV differentials are
located in the front of the vehicle right near the electric motors thus making FWD vehicles. Many FCPs employ the use of regenerative braking systems that increase the vehicle’s rate of recovery of energy and capacity to assist the fuel cell stack in powering the electric motor [2]. Fig.1 shows a parallel fuel cell hybrid powertrain layout while Fig. 3 shows a conventional ICE vehicle powertrain for comparison.

**Figure 1.** Fuel cell parallel hybrid vehicle powertrain. Adapted from [7].

**Figure 2.** Conventional ICE vehicle powertrain. Adapted from [7].

The fuel cell parallel hybrid is the most common type of fuel cell powertrain because it allows for the battery to act as an assistant to the fuel cell stack in powering the electric motor and can in turn be much smaller than the battery required for the series hybrid type in which the battery provides all the power for the electric motor 100% of the time [7]. The PEMFC powerplant consists of a stack of multiple cells. A typical cell is pictured below in Fig.3.

**Figure 3.** Diagram of a single PEMFC. Adapted from [8]. Each cell consists of a membrane electrolyte assembly (MEA) comprised of a polymer electrolyte membrane (PEM), catalyst layer (CL), micro-porous layer (MPL), gas diffusion layer (GDL), and flow field or bipolar plate. The PEM is located at the center of the cell and has two catalyst layers (CLs) bonded on each side. The PEM and CLs are in turn sandwiched between two porous gas diffusion layers that are connected to the flow field [1]. The fuel cell is supplied with reactant gas as shown in Fig.4.

**Figure 4.** Diagram of simple fueling system for fuel cell. Adapted from [7].

An electric motor drives a compressor at the air intake of the vehicle and is open to the atmosphere to supply the fuel cell stack with oxygen as well as drive the flow for the vehicle exhaust. An electric cooler and humidifier are used to cool the air before entering the stack. The hydrogen gas stored in a high pressure tank is supplied to the fuel cell stack by a pressure regulator [7]. The DC current output from the fuel cell stack is converted to three phase AC by a three phase inverter. In this type of inverter, six switches, with freewheeling diodes connect to a three phase transformer [7].

The two most popular types of batteries for FCPs are the lithium ion (Li-ion) battery and the nickel metal hydride (Ni-Mh) battery [4]. There are many types of electric motors that are utilized in FCPs including brushless DC (BLDC), AC induction, and switched reluctance (SR) motors. The BLDC motor is the most popular electric motor for electric vehicles and is also sometimes called the permanent magnet synchronous motor [7]. The three basic components of a BLDC motor are the rotor, stator, and coil [7]. A schematic of the basic BLDC motor is pictured in Fig.5.

**Figure 5.** Diagram of BLDC electric motor components. Adapted from [7].

The rotor is a permanent magnet and rotates. The stator is made up of stationary permanent magnets that are magnetized due to current flowing through the
coil. The stator in Fig. 5 is made up of a single magnet with two poles, north and south (N and S). To minimize the unsteady torque pulses caused by using a single coil, electric car motors often use a circular arrangement of multiple coils that surround the rotor [7]. There are multiple ways to transfer the mechanical energy output from the electric motor to the wheels. These methods include placing motors on four corners of the vehicle that put power to each wheel or using the conventional gearbox that puts power to both wheels in a FWD or rear wheel drive (RWD), or all wheel drive (AWD) application.

LITERATURE REVIEW

The inventor of the first fuel cell was William Grove, a lawyer and scientist in 1839 who experimented with electrolyzing water into hydrogen and vice versa. He found that a small current was produced when performing a reverse electrolysis experiment where hydrogen and oxygen recombine to produce water [7]. The very first PEMFC was developed in the 1960s in the United States by General Electric. Its purpose was to provide electricity and water to astronauts aboard NASA spacecraft like the Gemini[7]. These early PEMFCs had short lifetimes of around 500 hours and were very expensive to make due to their requirement for a large loading of platinum catalyst. Therefore, cheaper more reliable fuel cells at the time like the phosphoric acid fuel cells (PAFCs) and alkaline fuel cells (AFCs) were employed by NASA for further spacecraft such as the Apollo vehicles [7]. It wasn’t until the late 1980s that PEMFC technology made a comeback mainly through the work of Ballard Power Systems and the Los Alamos National Laboratory in reducing the platinum loading by a factor of 100 [7]. PEMFCs are now the preferred option for NASA spacecraft and are viewed as one of the superior possible electrical energy generating devices of the future due to their wide range of applications [7].

Honda has been one of the most outstanding automobile companies with respect to current advancements in automotive PEMFC powertrain technology in everything from stack design to electric motors. They released a 2005 model vehicle called the FCX and developed a revolutionary fuel cell stack in 2006for the 2007 FCX Clarity vehicle called the V Flow. The stack is a single rectangular box that is mounted vertically in the FCX Clarity’s center tunnel area behind the vehicle engine bay and boats a power output of 100 kW (136 hp) [2]. The stack vertical position in the vehicle allows for an increased ability to drain water and in turn reduces heat mass. This feature enhanced low temperature start up capabilities of the vehicle [2]. The vertical orientation of the flow path for the gases and water was a result of the design goal of making the stack more compact. A more compact stack meant reduced thickness in the channels that supply the reactant gases and also dispense of the water produced. As the flow channel depth is decreased, the water adhesion force to the channel wall will increase. Therefore orienting the channels vertically allows for gravity and the channel pressure difference rather than just the pressure difference alone in a horizontal application to help counteract this force.Therefore it allows for substantial channel depth reduction by 17% from the previous Honda FC stack design [2]. The development of wavy reactant gas supply channels allowed for a greater generating surface area to be covered than when using straight channels. This in turn allowed for a more uniform supply of reactant gases to the cell and a 10% increase in generating performance against the previous straight channel design [2].

With the design goals of increased compactness, higher efficiency, and increased power and speed in mind, Honda developed a cutting edge electric drive unit for the FCX Clarity called the MCF31 [4]. The motor puts out 100KW (136 hp) and allows for the vehicle to travel at the 160 km/h (100 mph) design target as well as achieve a maximum motor torque and speed of 256 Nm (189 lb-ft) and 12,500 min⁻¹ respectively. The 100 W (136 hp) power output is fully available from a speed of 48 km/h (30 mph) speed to a speed of 129 km/h (80 mph) and the vehicle has a passing acceleration performance comparable to a 2.4 liter (147 in³) gasoline powered vehicle [2]. This torque allows the vehicle to hold itself on an incline with only the throttle being applied slightly. The more compact design was feasible due to the integration of the electric motor, gearbox, and power drive unit all into one drive unit. This integration required the vibration created by the electric motor to be reduced as well as the vibration resistance of the power drive unit to be increased[2]. Also, a coaxial configuration of the motor and gearbox was achieved by making the rotor shaft of the motor hollow while the drive shaft to the gearbox and vehicle wheels is inserted inside the motor rotor shaft. This integration of components greatly reduces the overall length of the drive unit by 162 mm (6.4 in) from the 2005 MCF21 unit [4]. The external diameter of the motor was also reduced by 4% and the height of the unit was reduced by 240 mm (9.5 in) due to the integration of the motor gearbox, and power drive unit. The way the motor and gearbox are lubricated in the new design improved the overall operating efficiency by reducing friction [2]. Because the motor and gear box were housed separately in the MCF21 unit, the bearings of the electric motor and gear box were lubricated with grease and gear oil respectively. The new integrated components of the MCF31 unit allowed for less seals and only gear oil to
be used for bearing lubrication as new bearings were developed to work in this manner. A 36% reduction in friction from the MCF21 to the MCF31 unit was therefore achieved by this design change. The stator windings are able to be kept at a uniform temperature from using gear oil as opposed to grease and therefore allows for the power requirement to be met as well as the range of continuous operation to be met [2].

A new interior permanent magnet (IPM) synchronous BLDC electric motor was designed for the unit and has the ability to employ reluctance torque. The rotor used in the MCF31 motor was designed to spin faster and make more power than that of the MCF21. The inductance was optimized and in turn allowed for the current that is required to weaken the field of the drive for high motor speeds to be minimized. This, in turn, allowed for the reluctance torque to be used most effectively and for the power output to be increased [2]. The yoke strength of the rotor had to be strong enough to handle the centrifugal force due to the faster speed of the new motor as well as the increased number of magnets per pole. Therefore, strength analyses were conducted on two existing rotor designs. The first was a surface permanent magnet (SPM) from the MCF21 unit while the second was an IPM magnet used in Honda Accord hybrid model [2]. The SPM rotor allows for the magnets to be positioned close to the stator core therefore allowing for the magnetic resistance on the axis of the flux field to be increased. This in turn allows for the inductance at this axis to be set low and therefore increases power. This type of rotor would allow for the torque and power targets to be met however the faster speeds and large centrifugal force were too large for this type of rotor to sufficiently withstand. The IPM rotor featured a special yoke that has a center rib that divides the magnets in two and could carry the load needed. However, the magnetic resistance is decreased with this type of rotor and the target power and torque requirements could not be met. Therefore a new rotor design incorporating both existing rotors was sought after. The result was a rotor with a center rib that used the type of half moon shaped magnets of the SPM rotor. This new rotor type was able to meet the power and torque requirements and also achieve a fracture strength of 23,000 min⁻¹ [2].

OPERATION OF THE TECHNOLOGY

The operation of a single cell in a PEMFC stack is outlined in Fig. 3. Hydrogen gas is pre-humidified and supplied on the anode side of the cell. The hydrogen diffuses through the GDL and oxidizes into two hydrogen protons and two electrons when it reaches the catalyst layer. The hydrogen protons in turn are conducted across the membrane and the electrons are conducted back towards the flow field. The flow field in turn passes the electrons away from the cell through an external load and then back to the flow field on the cathode side. The cathode side flow field conducts the electrons to the cathode GDL and in turn to the catalyst layer. The cathode flow field also supplies the cell with air from the vehicle intake. The oxygen in the air is diffused through the GDL to the cathode catalyst layer where it is reduced with the hydrogen protons and electrons to form water. This water is then transported back through the GDL and out the exhaust port of the flow field and in turn out of the stack. The external load that the electrons from the anode flow field are conducted through consists of a bi directional DC/DC converter, inverter, electric motor, and battery. The electrical power that is outputted from the fuel cell stack is not at a suitable and constant voltage for the battery [7]. The DC/DC converter coupled with subsidiary voltage regulators and chopper circuits are used to manage the uneven voltage produced from the stack and in turn bring it to a fixed value [7]. The DC/DC converter aids in starting the fuel cell stack and boosts the low voltage up to a 50:1 ratio for 5 to 20 seconds during start up [9]. Powering the compressors for the reactant gases and exhaust and requires up to 3 kW of power at start up. After the stack is started, the DC/DC converter is used to convert power produced from the stack to recharge the vehicle 12 VDC battery [9]. Under normal operating conditions, the device is required to maintain 2 kW of regulated power over the range of 13.3-14.4 VDC [9]. The battery stores the electrical energy produced by the fuel cell and discharges it on demand to the inverter which converts the DC current to alternating current (AC) via a circuit of four switches called a H-bridge. This circuit is pictured below in Fig. 6.

![Figure 6. A basic H-bridge circuit diagram used for creating single phase AC current. Adapted from [7].](image)

First, switch A and D are turned on and current flows to the right through the load which is represented in Fig. 8 by an inductor and resistor [7]. After switches A and D are turned off, switches B and C are turned on and the current flows to the left. This switching
process is repeated and thus produces a single phase AC current [7]. For most automotive electric motors, three phase AC supply is needed and the circuit in Fig. 8 would have six switches and the addition of a three phase primary transformer [7]. The AC current that is output from the inverter is then passed through an AC electric motor. In the case of the FCX Clarity and most other electric vehicles and FCVs, this motor is the brushless DC motor. It is called a brushless DC motor because it requires a DC power supply. The operation of a simple single coil brushless DC motor is pictured in Fig. 7.

Figure 7. Diagram of a basic brushless DC motor operation. Adapted from [7].

In part A of Fig. 7, the current flows in the direction that allows for the stator to become magnetized and in turn make the rotor spin clockwise. In part B when the rotor passes through the poles of the stator, the switches are turned off and then the momentum of the spinning rotor carries it on until it rotor reaches the angle shown in part C. This is where the current is reversed and magnetizes the stator to keep turning the rotor in the clockwise direction [7]. Hall-effect sensors are often used to control the current switching process and they use the magnetism of the rotor to sense its position [7]. This basic theory of operation can be applied to an electric motor with a circular arrangement of multiple coils and poles with only a different circuit of switches. All these components work together to form fuel cell battery hybrid systems like those pictured in Fig. 1 and Fig. 2. The fuel cell hybrid system orders the fuel cell to work continuously at close to its maximum power at all times. When the total system power requirement is low, the excess power generated by the fuel cell is in turn stored in the battery. Then, when the power requirements exceed that of which the fuel cell cannot supply by itself, the battery is discharged to provide the supplemental power needed [7]. Some FCV platform may also incorporate using the motor as a brake. A BLDC motor along with many others can also function as a generator and can be employed to do so during braking of the vehicle. This process is called regenerative braking in which mechanical energy is converted back into electrical energy and in turn to the battery to be later used to power the electric motor [7]. Fig. 8 shows a diagram of an entire fuel cell battery hybrid system that also incorporates regenerative braking. The bold arrows show the directions in which energy flows throughout the system.

Figure 8. Diagram of energy flow directions in a typical fuel cell parallel hybrid vehicle powertrain. Adapted from [7].

**THEORY OF THE TECHNOLOGY**

There are many factors that influence the performance and efficiency of a fuel cell powertrain. The performance of a fuel cell is measured by a polarization (I-V) curve generated from plotting the fuel cell’s voltage in volts (V) versus the current per geometric electrode area, A, or current density, j, in amperes per square centimeter (A/cm²) [1]. The equation for current density is as follows in Eq. (1).

\[ j = \frac{I}{A} \]  

A typical polarization curve is pictured in Fig. 9 below.

Figure 9. Polarization, curve, waste heat generation, and useful electrical power curve as well as the three regions. Adapted from [1].

The curve can also be plotted as power per unit of geometric electrode area or electrical power density versus the current density. The equation for power density is as follows in Eq. (2).

\[ P_e = \frac{P}{A} \]  

There are three different regions of the I-V curve. The first region, called the activation polarization, is of high voltage and low current density and represents the voltage required to overcome the activation energy of the electrochemical reaction on the catalytic surface of the catalyst layer [1]. The second region occurs at moderate current densities and cell voltages and is
called the ohmic polarization. Performance loss in this region is dominated by losses with respect to all ionic conduction losses through the electrolyte, catalyst layers, GDLs, MPLs, and flow fields. The more flat this region of the I-V curve is across the range of moderate current densities the better the cell performs during normal operation. It is clear to see that over the cell’s lifetime, this region depends on the electrical conductivity of the GDL and catalyst layer as well as the proton conductivity of the electrolyte. Also the fuel cell is typically run at the moderate current densities and voltages that are in this region so it is important that the components that directly affect this region do not degrade quickly when subject to normal operating conditions. The third and final region is called the concentration polarization and represents the upper current densities and low voltages [1]. Performance losses in this region are dictated by mass transport or flux of the reactants to the electrodes as well as water management. The mass transfer limiting current density is governed by this region and is the current density at which the rate of mass transport to the reactant surface is insufficient to promote the rate of consumption required for reaction. Thus the cell ends up having areas where the local concentration of reactant is reduced to zero thus reducing the cell voltage [1]. Also flooding, which is denoted by the starvation of the cell of reactant gases due to an excess amount of water in the GDL can be directly shown by an abrupt drop in the I-V curve after the ohmic region. With respect to the stack, the power produced, P, is a function of voltage, V, and current, I, produced as shown in Eq. (3).

\[ P = V \times I \times n \] (3)

Where \( n \) is the number of cells in the stack [7]. Efficiencies of the stack, motor, and cell all play a major role in the design and optimization of an automotive fuel cell powertrain. The efficiency related to the fuel cell itself is governed by Eq. (4).

\[ \varepsilon = \left( \Delta \tilde{g} \right) \left( \Delta H_{B, N} \right) \] (4)

\( \Delta \tilde{g} \) is equal to the change in Gibbs free energy, \( \Delta H_{B, N} \) is the change in enthalpy of formation, \( V \) is the voltage outputted by the cell, \( E \) is the open circuit voltage, or ideal voltage that can be produced by the fuel cell and \( \lambda \) is the stoichiometric factor. For example a value of \( \lambda = 1.5 \) would mean the cell is being supplied with 1.5 times the fuel needed for 100% fuel utilization [10].The torque output of the IPM electrical motor used in the Honda FCX Clarity that can use reluctance torque can be calculated using Eq. (5).

\[ T_\varphi = P_e \times \varphi \times I_q + P_n \times I_d \times I_q \times (L_d - L_q) \] (5)

The torque axis is defined as the q-axis and the flux field axis is defined as the d-axis for this equation. \( \varphi \) is the magnetic flux linkage of the magnet, \( P_e \) is the number of pole pairs (N and S) in the motor, and \( I_d \) and \( I_q \) are the currents at the d- and q-axes respectively. Similarly the inductances at the d- and q-axes are \( L_d \) and \( L_q \) respectively [2]. High motor speeds require the field to be weakened which sacrifices torque. The current required for field-weakening drive is defined in Eq. (6).

\[ I_d = -\frac{\varphi}{L_d} + \frac{1}{L_q} \frac{V_{in}^2}{\omega^2} - (L_q \times I_q)^2 \] (6)

\( \omega \) is the angular velocity of the motor shaft and \( V_{in} \) is the input voltage to the motor. A high inductance at the d-axis would in turn allow for the current at the d-axis to be reduced allowing for the field to be weakened [2]. However it is seen that this increase in inductance decreases the power output by the motor due to Eq. (7).

\[ P \propto V_{in} \times \frac{\varphi}{L_d} \] (7)

These three equations characterized the design of the motor for the FCX Clarity as described in the literature review section of the paper. Losses in the DC/DC converters are due to the fact that the currents through the inductor and switch are higher than the output current. The efficiencies of the DC/DC converters should typically be around 80% however efficiencies of 95% have been achieved [7]. Electric motors essentially convert electrical energy at the input and to mechanical energy at the output with some of the original energy being lost as heat. The electrical power at the input can be calculated by Eq. (8).

\[ P_{in} = VI \] (8)

The mechanical power at the output can be calculated by using Eq. (9).

\[ P_{out} = T \omega \] (9)

A rough calculation of the electric motor efficiency would be as follows in Eq. (10).

\[ \varepsilon = \frac{P_{out}}{P_{in}} \] (10)

However there is no internationally agreed method of stating the efficiency of an electric motor because there is a lot that can affect the overall performance. The size of the motor influences the efficiency and higher power motors are often higher in efficiency [7]. The second factor is the speed that the motor can operate at and the faster a motor can spin the more efficient it will be [7]. The method of cooling the motor also affects its efficiency. Liquid cooled motors allow for low temperature operation and therefore create less resistance on the windings [7].

**DISCUSSION**

It is plain to see that automotive PEMFC powertrains can allow for much more degrees of freedom in the layout of the powertrain in the vehicle. They utilize a renewable fuel and can in turn reduce our dependence on oil. There are less moving parts in a fuel cell powertrain than there are in a conventional gasoline IC engine powertrain and therefore less maintenance. Although fuel cells have been around since the 1800s,
only now with the advancements in platinum loading and successful public market tests like GM’s “Project Driveway” have the advantages of the technology come to the surface. Hydrogen however does not occur in nature and is also not easy to make. No large infrastructure to fuel these new breed of cars exists yet. The United States Department of Energy has a fuel cell technologies program that funds an array of research areas related to the many different barriers that impede the development of hydrogen and the deployment of fuel cells [11]. Although General Motors went bankrupt, their fuel cell research program was never stopped and they intend to keep researching the technology [3]. Innovations will continue to be made in all aspects of fuel cell powertrain technology because every component counts towards improving the overall robustness and efficiency of the system. A great example of these types of innovations are showcased in the development of Honda’s FCX Clarity FCV. It’s research like this that will push the fuel cell powertrain closer to the public market.

CONCLUSIONS AND RECOMMENDATIONS

I believe there is an opportunity for the development of fuel cell powertrains in public vehicles due to both the economic concerns of using a nonrenewable fossil fuel as the main fuel for current vehicles as well as the polluting effects these conventional vehicles have on our environment. The external constraints that prohibit this technology from becoming mainstream are the hydrogen fuel, the refueling infrastructure, the cost and durability of the fuel cell powertrain itself, and the limited range that the vehicles have between refueling time. The reliability of the IC engine coupled with the vehicle range that can be achieved through its use in a gas/electric hybrid vehicle creates a tough competitor for the FCV to surpass. Therefore I believe that the key research areas are within the powertrain durability, hydrogen storage both onboard the vehicle and at the pump, hydrogen fuel production, and fuel infrastructure realms. The fuel cell powertrain allows for engineers to think outside the box and configure the components in new locations throughout the vehicle chassis. They can, in a sense, redesign the automobile. Weight distributions can be further optimized due to the increased degree of freedom in this area. When the level of durability of the FCV reaches an adequate point, the maintenance would be much easier than a conventional IC engine vehicle as there are less moving parts. The stack can be much more easily removed than an engine and the downtime of the vehicle would be surely mitigated. It is because of these advantages that fuel cell powertrain related projects are in the research and development labs of all the major automobile manufacturers. The pollution of our planet by the ever increasing amount of automobiles that are used on it along with the nonrenewable fossil fuels they utilize calls for a clean and renewable fueled vehicle to become the mainstream vehicle used. The fossil fuels currently combusted in IC engine vehicles today will eventually run out and we need to be prepared when that time comes to ensure that our transportation industry can thrive like it does today. Also fossil fuels need to be used for other useful things such as oil for machinery that manufacturer not only our current cars but our food and other things we use on a day to day basis. If the current research innovations keep being made, like Honda has demonstrated with the FCX Clarity, the vehicles of tomorrow could most likely have a smooth, efficient, environmentally friendly, and cost effective PEM fuel cell powertrain. If this occurs along with allowing for the fuel to be produced efficiently and an adequate fueling infrastructure to be put into place, we will have eliminated our dependence on oil.

REFERENCES
THEORY AND OPERATION OF MAGNETO RHEOLOGICAL FLUID CLUTCH

Masoud Golshadi
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

The function of the clutches in powertrain systems are to transmit the engine torque to the gearbox and prepare the opportunity to engage or disengage the gears by mechanically connecting and disconnection the transmission of the torque. There are two different type of clutches; the friction clutches and the torque converter. Because of the high wear rate and huge lag time in friction clutches, which are suing in manual and semi-automatic transmissions, the durability of them are very low and the wearout of the materials which has been used in them, are very dangerous for the environment. In the other hand, the automatic transmissions, which are using the torque converter, don’t have the same amount of excitation of manual gearboxes, especially for sports cars. So, for the high performance vehicles, the clutches with very fast reaction time, with high level of durability and without any wear are required. The magneto-rheological fluid clutches are the answer to this necessity.

This paper is aimed to explain the theory and operation of MR fluid clutches by starting from basic description of MR fluids. Then the operation of the totality of the system is described and it will be continued by detail explanation of the parts and pieces of the clutch. Then the output torque of the clutch is driven by utilizing the Bingham plastic model for MR fluids. At the end, some problems like centrifugal effect of the particles and the amount of the output torque are addressed as the obstacles in front of the technology and some recommendations are provided to combine the system with traction control or using dual clutch phenomenon to increase the performance and solve the addressed problems.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Magnetic Flux</td>
<td>(Wb)</td>
</tr>
<tr>
<td>I</td>
<td>Current</td>
<td>(Amp)</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
<td>(N.m)</td>
</tr>
<tr>
<td>g</td>
<td>Gravity Acceleration</td>
<td>(m/s²)</td>
</tr>
<tr>
<td>r</td>
<td>Radius</td>
<td>(m)</td>
</tr>
<tr>
<td>u</td>
<td>Velocity as a function of y and r</td>
<td>(m/s)</td>
</tr>
</tbody>
</table>

Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega )</td>
<td>Angular velocity</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Shear stress</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Viscosity</td>
</tr>
</tbody>
</table>

Subscripts & Superscripts

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR</td>
<td>MR fluid</td>
</tr>
<tr>
<td>in</td>
<td>Input</td>
</tr>
<tr>
<td>out</td>
<td>Output</td>
</tr>
<tr>
<td>vis</td>
<td>Viscous</td>
</tr>
<tr>
<td>P</td>
<td>Plastic</td>
</tr>
<tr>
<td>y</td>
<td>Normal distance from the plate</td>
</tr>
</tbody>
</table>

BACKGROUND

Magneto-rheological (MR) fluids consist of finely powdered ferromagnetic particles such as iron or iron alloy in a fluid carrier like mineral oil or silicone. Thus, under the magnetic field, these fluids exhibit a controllable shear yield stress. A magneto-rheological fluid clutch consists of clutch plates and this kind of fluid in between them. The plates are made of material with high magnetic permeable characteristic and some devices have the responsibility to produce desire level of magnetic flux through them and the fluid.

In recent years, MR fluids are being considered in variety of energy dissipation and torque transfer devices such as shock absorbers, clutches, brakes and engine mounts. MR fluid clutches are distinguished by very good controllability of transmitted torque, very short reaction time and little wearout. The fundamental advantage over traditional clutches consists in their ability to process electric control information directly, i.e. without any mechanical links. The activation of MRF clutch’s built-in magnetic field causes a fast and dramatic change in the apparent viscosity of the MR fluid contained in the clutch. The fluid changes state from liquid to semi-solid in less than 6 millisecond. The result is a clutch with a infinitely variable torque output [1].
DESCRIPTION OF THE TECHNOLOGY

The MRF clutch is a complete replacement of the regular friction clutches and it will be positioned in between the engine and drive shaft in rear wheel drive cars, or in between the engine and differential in front wheel drive cars. Figure 1 illustrates all pieces and parts of the system. The ECU 3 (electronic command unit), has been connected to the driver command lever 1 through wire 2. The battery 7 has been connected to the electromagnet coil 8 via wire 6 and switch 4. The switch 4 will be activated by ECU through wire connection 5. Electromagnet bobbin 9 has the responsibility of producing magnetic field inside the clutch MR fluid 10. The input shaft 11 gets the torque from engine and it will transfer it to the output shaft 12. The wire 13 takes the output torque through sensor 14 and gets the info back to ECU 3 as control feedback.

Figure 1. Overall illustration of all parts and pieces of the system

The Fig. 2 shows the MR fluid clutch in more details. The blades 21 are connected to the input shaft 11 and the blades 20 are connected to the output shaft 12. The MR fluid 10 is prevented from leakage with two seals 18 and 19. The stationary cores 15 and 16 support the bobbin 9, core ring 17 and the coil 8 in their positions. The stationary cores 15 and 16 should be made of an efficient magnetic permeable material such as iron or steel to carry the electromagnetic field. The air gap 22 in between the input and stationary section is for transferring the heat which has been created inside the fluid and the coil.

Figure 2. Detail illustration of the parts and pieces and parts of the MR fluid clutch

Usually there are two main designs of the MRF clutch with basic shapes. The “Disk shape” like figure 3 and the “Bell shape” like figure 4. Both consist of two rotatable parts with a small gap in between connected to the input respectively output shafts. This gap is filled up with MRF which transmits the power by interaction of the surfaces and the fluid. Although the aforementioned designs are very popular, the performance of the clutches with respect to the power density, temperature behavior and the drag torque has room for improvement [2].

Figure 3. Disk shape MRF clutch

Figure 4. Bell shape MRF clutch
LITERATURE REVIEW


In automotive industries, General Motors and other automotive companies are seeking to develop a magneto-rheological fluid based clutch system for push-button four wheel drive systems. This clutch system would use electromagnets to solidify the fluid which would lock the driveshaft into the drive train.

OPERATION OF THE TECHNOLOGY

According to the figure 1, the system starts its action by a command from driver through a pedal or flappy paddle 1. Then the command will transfer by wire 2 to the ECU 3. Then the ECU will activate switch 4 with wire 5 and it causes the circuit 6 bring electric power from battery 7 to the electromagnet coil 8. Then, electromagnet core 9 produce magnetic field by utilizing the current from the coil and it causes the MR fluid 10 to change its state from liquid to semi-solid. So, the input torque from 11 will transfer to the output disk 12 via shear stress inside the MR fluid. Increasing the current will increase the amount of transferred torque and decreasing the current will decrease that torque. The system can get the feedback information from sensor 14 though wire 13 to ECU and compare input and output torques to apply enough current at electromagnet coil in terms of controlling the output torque for different situations.

THEORY OF THE TECHNOLOGY [1]

In order to derive the output torque equation for this clutch, the Bingham plastic model is used as the constitutive equation for behavior of the MR fluid. Bingham plastic model gives the shear stress as Eq. (1).

\[
\tau = \tau_y \cdot \text{sgn} \left( \frac{\partial u}{\partial y} \right) + \mu_p \frac{\partial u}{\partial y} \tag{1}
\]

\(\tau_y\) is a function of the magnetic field while \(\mu_p\) is assumed to be constant. The first part of the right hand side of the Eq. (1) produces a torque, which is dependent on the magnetic field, and a second term generates a viscous torque. Therefore, the total output torque can be expressed as the Eq. (2):

\[
T_{\text{out}} = T_{\text{MR}} + T_{\text{vis}} \tag{2}
\]

Derivation of MR torque requires the relationship between MR fluid shear yield stress and the applied magnetic flux density. This relationship will be obtained from the manufacturer’s data sheet for the commercial MR fluid.

Since the magnetic field is a function of radial location, shear yield stress can be determined as the function of the plate radius. For a given yield stress distribution, the output torque can be obtained by Eq. (3).

\[
T_{\text{MR}} = 2\pi \int_0^{r_0} \tau_y(r, B) \text{sgn} \left( \frac{\partial u}{\partial y} \right) r^2 \, dr \tag{3}
\]

For small gap between the plates, one can derive the tangential fluid velocity by assuming no slip condition and linear velocity distribution as Eq. (4).

\[
\frac{\partial u}{\partial y} = \frac{r \Delta \omega}{g} \tag{4}
\]

Differentiation of Eq. (4) with respect to \(y\) gives the shear rate as Eq. (5).

\[
\frac{\partial u}{\partial y} = \frac{r \Delta \omega}{g} \tag{5}
\]

Then, the sign of shear rate can be written as Eq. (6).

\[
\text{sgn} \left( \frac{\partial u}{\partial y} \right) = \text{sgn} \left( \frac{r \Delta \omega}{g} \right) = \text{sgn} (\omega_{\text{in}} - \omega_{\text{out}}) \tag{6}
\]

Substituting Eq. (6) into Eq. (3) give the Eq. (7):

\[
T_{\text{MR}} = 2\pi \text{sgn} (\omega_{\text{in}} - \omega_{\text{out}}) \int_0^{r_0} \tau_y(r, B) r^2 \, dr \tag{7}
\]

By numerically integrating Eq. (7), MR torque equation for the yield stress function for a given input current, output torque versus input current relationship is derived. Similarly, the viscous torque can be derived as Eq. (8).
Based on the dimensions and material properties, the viscous torque is determined to be very small compared to MR torque. Therefore, viscous effect can be neglected in the total torque output equation. Then the total torque for MRF clutch can be written as a function of input current like Eq. (9).

\[ T_{\text{out}} \equiv T_{\text{MR}} = c_1 I^2 sgn(\omega_{in} - \omega_{out}) \]  

(9)

Where, \( c_1 \) and \( c_2 \) are the constants obtained numerically using electromagnetic FEA.

DISCUSSION

Due to necessity to have a faster gear change, higher durability, higher torque transfer, flexibility to combine the system with other systems and the packaging issues, they all tend the automotive industries toward using the MR fluid clutches which have all of these characteristics. Especially when we talk about high performance vehicles or super sport cars; and these are the reasons for inventing the DCT (Dual-Clutch Transmission) systems and new 7 gear automatic gearboxes with active clutches. But, for each application, the proper MR fluid must be used and in some cases, some research is needed to produce proper MRF for a specific product. In the other hand, the clutches are used in different industries and transferring the torque in a smooth way and without any vibration is very important in some applications, such as fans, and the MR fluid clutches can satisfy this requirement, too. Thus, the future of this kind of clutches are very bright and this technology, and especially the usage of MR fluids, will change the shape of the future transmission systems.

In the way to achieve these goals, the General Motors and some other companies, are working on the new drive-train system for 4WD cars to lock the driveshafts to each other and the Porsche is working on new engine mounts for their 911 models based on the MR fluids in its R&D center. Improvement of the technology for novel MR fluids, cause to improve the capacity onto the road. Thus, in MR fluid clutch, by applying less current for electro magnets, the magnetic field will reduce and the proper amount of torque will transmit to the main shaft. This system can dissipate less energy than the TC systems which applying the brakes and it will be cheaper that the systems which suppress the engine spark to one or more cylinder.

2) Using the Dual MR fluid clutches: The dual clutch transmission (DCT) is one of the new technologies in sports cars world. The DCT system is a combination of the two separate manual gearbox in such a way that one of them controls the odd and the other one controls the even gears. By substituting the MR fluid clutch instead of the friction clutch in this systems, we can even decrease the reaction time more and more and this system can prevent the centrifugal effect of particles due to connecting and disconnecting the clutches to use the other.

REFERENCES


THE EFFECT OF THE JAPAN TSUNAMI AND EARTHQUAKE ON THE AUTOMOTIVE TRANSMISSION INDUSTRY

John Janiszewski
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
On March 11, 2011 an earthquake occurred off the coast of Japan. The earthquake as well as the resulting Tsunami created large amounts of devastation throughout the country. This devastation sent ripples throughout the automotive industry as companies began to worry whether or not they would be able to get shipments of parts from Japan needed in the construction of their transmissions. It was expected that companies based in Japan would be hit hard but what effect would this disaster have on the automotive giants of the United States. By looking at the number and types of products made in Japan for the Automotive Transmission Industry as well as the amount of production done yearly and quarterly a proposed outlook as to the effect this will have on the industry can be created.

This outlook can be expanded and adapted as the situation continues to evolve allowing investors as well as the companies affected can change and adapt their business plans to deal with the situation. This paper sets out to analyze the history of the components affected in terms of production in Japan, who and what this problem is affecting and how much they are being affected and what plans could be implemented in the future to avoid a similar situation.

BACKGROUND
Japan is a major center for the automotive industry in terms of manufacturing. Japan houses many assembly plants for Toyota, Nissan, Honda as well as component manufacturing for General Motors, and Renault. Toyota’s engine and transmission production for the 2010 year was 1,246,654 units [1].

Honda’s production in 2010 for automobiles is described in Image 1 below. As can be seen from the image their complete production was about 3.6 million units. [2]

Nissan’s production and sales for the 2010 year came out to be 1,023,638 units. Their projection prior to the natural disaster in Japan was 1.15 million units in 2011. [3]

While these are the three main manufactures based in the Asian market the situation also affects General Motors, and Renault. In 2010 General Motors sold 24,642 Chevrolet Colorado’s and 7,992 GMC Canyon’s. These two vehicles require transmissions that either requires components from manufacturing plants in Japan or the whole transmission assembly from Japan [4].

Renault imports engines and transmissions for Samsungs SM7 saloon car and for the majority of its vehicles. In 2010 Renault sold 2.6 million units with the majority of those being sold in Europe. [5]

It can be seen that between these five companies the total amount of units sold is around 9 million. That is the majority of the automotive market throughout the world. Having these companies affected for a long period of time can have a long lasting effect on how the automotive industry performs this year and how long it will take for them to recover.

DESCRIPTION OF THE SITUATION
With General Motors outsourcing its pickup truck transmission construction to Japan they are currently cutting back and shutting down plants in
order to not run out of stock. Current estimates suggest that they will halt production at their Louisiana plan this current week as well as possibly stopping work at two European plants as well as possibly one South Korean plant. [6]

Early estimates state the global automotive market has lost 320,000 vehicles with a possibility of losing up to 5 million vehicles worldwide. Ford is cutting back hours in its Dearborn, Kansas City and Avon Lake plants for lack of parts. They believe that the time period between April 22nd and May 6th will be the crucial time period to determine the overall effect this disaster has on the global economy. [7]

Early estimates had put Honda having its Japan manufacturing plants shut down till the start of April as well as some of its North American Plants being shut down till the 26th of March. Toyota’s initial evaluation of the situation was that there would be little effect on the industry as they had a lot of parts stockpiled prior to the disaster occurring. However they were forced to suspend production on Mondays and Fridays from April 15th through June 3rd due to parts shortages.[8]

Nissan was set to close at least some of its plants due to the shortage of parts for almost a week in mid April. The engine plant in Fukushima was damaged and shut down till April 17th while the rest of the manufacturing plants for Nissan were down until March 23rd. In the first week after the disaster all of the companies affected were struggling to try and figure out whether or not they truly would be affected and how much they would be affected.

CURRENT ASSESSMENT OF THE SITUATION

Now into the month of May fully two months after the disaster occurred the situation for each manufacturing company has really started to take shape. Toyota has been running the majority of its Japanese plants as well as its North American Plants at approximate 50% for the past few weeks. While there are still shutdowns that have occurred the company just released good news that they expect to be boosting production up to 70% in June which is 30% higher than they are currently running.[9] The hope is that by July or early August the company can return to full production. Toyota expects its Japanese plants to return to full production sooner than those in North America due to the sipping time it takes for the components needed to be shipped to the North American plants. Toyota will still suspend production in its Canadian plants the week of May 23rd which coincides with the Victoria Day holiday as well as the week of May 30th for its United States plants in accordance to the Memorial Day holiday. These are scheduled shutdowns and do not affect the overall output of the company. Toyota has been the hardest hit out of all of the Japanese automakers loosing approximately 100 billion yen due to the disaster that has occurred in Japan. This is mainly due to a 250,000 unit loss during the fourth quarter.

As of April 11th Honda’s facilities in Saitama and Suzaka had resumed production at about 50%. This plan is set to stay in place till the end of June. The hope is as with Toyota that they can begin to return to normal production around July and August.[10] In the images below it can be seen that there is a difference between the projected numbers on January 31, 2011 and the actual numbers reported at the end of March due to the disaster.

![Graph showing difference between projected and actual earnings](image)

(Nissan estimates that they have lost 55,000 units just in the month of March. Nissans plan is to periodically halt weekend shifts in Mexico, the U.S and the UK as well as China. The goal is to move more of the production into its China and US markets in order to try and halt market losses by the end of the year. Currently in the 4th quarter Nissan has lost 39.6 billion yen. [11]

SUGGESTIONS

When looking at the companies involved in the disaster and how each one was affected it was easy to determine what the main factor was and that was distance. The companies that were father from the disaster and had the least amount of suppliers located in the disaster zone were the ones who were the least affected. Both General Motors and Ford have diversified their suppliers, manufacturing facilities, as well as assembly plants throughout the world market making use of the North American market, the Asian market as well as the European market. Because of this the effect the disaster had on their operations was
very limited and they were able to maintain normal production.

The difference can also be seen just between the three Japanese automakers. Honda has approximately 80% of its engine and transmission departments in the United States. Toyota also boasts of 14 different manufacturing plants and assembly plants throughout the United States. Because of this they were able to transfer the bulk of their production to these facilities and continue to run them at 50% while they were attempted to recover and restart their facilities located in Japan. This allowed them to set a more aggressive recovery plan to have their plants up and running at 100% by July while Nissan is only projected to get their plants to full capacity by October. In the automotive world having a full two months of production on your competitors can mean a lot in terms of sales and profit come year’s end.

When looking at this disaster, the reaction to it by all of the parties involved, and the aggressive nature as well as the amount of time and effort put into recovering these operations two suggestions come to mind. The first suggestion being that all automotive manufacturing companies need to expand to more global markets. They can do this a couple ways: they can build new manufacturing sites in areas that they have not done before preferably closer to the suppliers that they have. The second is that they can invest in suppliers located either closer to their manufacturing plants or on a more global scale. This allows the company to diversify where they get their parts from, how many different companies they get their parts from, and the speed at which they get their parts. By doing this it reduces the chance that the whole operation will be halted by not having a part needed in assembly because another situation like this had occurred where your only supplier of that part was located. This also allows for the global economy to grow as new jobs will be created not only here in the United States but around the world in the other markets.

The second suggestion that can be made is to take everything they have learned from this disaster in terms of initial reaction, to situation assessment, and finally recovery plan and begin to formulate a plan that will be able to do this better. By learning from this disaster and setting up a plan that anticipates another situation like this they may be able to take what is now a 4-6 month recovery time and turn it into a 2-3 month recovery time effectively increasing their productivity for the year as well as their profits.

CONCLUSIONS

As the year continues to unfold the picture of the industry will become clearer and clearer. With the power plants still being unstable and the recovery effort still moving slowly in Japan the lingering effects this will have on the industry has yet to be seen. When doing research over the past two months almost weekly the reports were changing sometimes quite drastically. If the companies are able to return to full production between the July-October time period they still stand to lose possibly as much as one full quarter of production. According to the Automotive News over 500,000 units were not produced during the first month after the earthquake. This loss alone translates into a $24.6 million dollar loss per day for the industry. If this continues for three months the industry could look to lose over $22 billion dollars. [13]

This means two things for the automotive markets for this year. The first being that the US and European automotive markets will continue to grow stronger in terms of production as well as sales. This is because it will take time for Japan’s infrastructure to recover from the earthquake and even though production may resume to 100% by the end of the year in Japan the ability to sell the same amount of vehicles prior to the disaster will be severely limited. Also because companies like General Motors, Ford, BMW and others were not affected by the disaster they were able to maintain normal production which lead to General Motors posting a $3.2 billion dollar profit in the first quarter for the year of 2011 with $36.2 billion dollars in revenue. This is $2.3 billion dollars more in profit than the first quarter of 2010 and $4.7 billion dollars in revenue more than the first quarter of 2010.

Ford was able to post increased revenues and profits for the first quarter of 2011 with numbers that rivaled those of General Motors. Fords first quarter revenue was $33.1 billion which was an 18% increase as well as being higher than the $30.5 billion that the analysts were projecting. Throughout the whole disaster in Japan Ford has only lost production on about 12,000-14,000 units which has allowed them to continue to bring in higher profits.

The longer the Japanese automakers take to recover from this disaster the stronger the other markets will become which will change the landscape of the automotive industry for the next few years.

REFERENCES

million-vehicles-amid-Japan-disaster-expert-says?odyssey=tab
THEORY AND OPERATION OF CONTINUOUSLY VARIABLE TRANSMISSIONS

Matt Koppey
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
The continuously variable transmission has become a practical option for most passenger vehicles within the past decade. In the coming decade it is expected to become even more prevalent throughout the world. For this reason, this paper intends to explore the parts and underlying theory behind the operation of a specific type of CVT, the Van Doorne Pushbelt. This type of CVT is the most common type found in passenger vehicles. It appears that CVT technology will experience a majority of its growth in the compact and hybrid vehicle markets in Japan and China with moderate growth in the US.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Moment of inertia</td>
<td>(m^4)</td>
</tr>
<tr>
<td>R</td>
<td>Transmission ratio</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
<td>(N∙m)</td>
</tr>
<tr>
<td>r</td>
<td>Pulley radius</td>
<td>(m)</td>
</tr>
</tbody>
</table>

Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Angular Acceleration</td>
<td>(rad/s^2)</td>
</tr>
<tr>
<td>ω</td>
<td>Rotational Speed</td>
<td>(rad/s)</td>
</tr>
</tbody>
</table>

Subscripts & Superscripts

d    Drag
l    Engine input shaft
m    Losses
o    Driveshaft out
p    refers to driving pulley
s    refers to driven pulley

BACKGROUND
As current automotive trends continue to move towards maximizing fuel economy by any means possible, the continuously variable transmission is poised to replace conventional automatic transmissions. By only offering a fixed number of gear ratios traditional gearboxes require a great deal of engine operation to occur at less than peak efficiency. Continuously variable transmissions effectively allow for an infinite number of gear ratios between the minimum and maximum values. The infinite amount of gear ratios ensures that the engine can operate much closer to the peak efficiency of the engine throughout the driving cycle. Until recently, CVT’s were only considered viable options for very small engines. New developments in both design and materials have allowed CVT’s to enter into the mainstream passenger car market. CVT production volume worldwide was estimated to be around 5.25 million units, with a majority of them coming from Toyota, Jatco, and Honda. Projections suggest that worldwide production will reach just over 7 million units by 2015. [1]

Nearly all major automotive manufacturers currently offer CVT’s as an option in many of their current model lines. Nissan in particular seems especially committed to CVT technology, having just sold over a million vehicles with CVT’s. They employ both the Van Doorne pushbelt style examined in this paper as well as toroidal designs in their vehicles.

Though this technology is far from new, inadequacies in materials had left CVT innovation somewhat stagnant for years. Within the last decade or so, materials have gotten to the point where this transmission design can really be used to it’s potential. Now that manufactured belts can withstand the loading of reasonably sized passenger cars the rest of
the technology is ready to get some well deserved attention and research.

DESCRIPTION OF THE TECHNOLOGY

The simplicity of a typical continuously variable transmission is another alluring quality. With the exception of various sensors, processors, and hydraulics, a CVT has only three main components. The input pulley receives power of the engine, when the clutch mechanism is engaged. The groove of the pulley is made by two eleven-degree sheaves that exist on a shaft. One half of the sheave is fixed, while the other is able to move along the axis of the shaft. As shown in figure 2, the input pulley connects to another “driven” or output pulley via belt. The driven pulley connects to the driveshaft, and functions in the same manner as the driving pulley, one half fixed, one mobile along the shaft axis.

Figure 2. Drawing depicting main components of a CVT. [2]

The connecting belts vary depending on application. Lighter applications like snowmobiles and large power tools utilize high density rubber V-belts, while automotive CVT’s have begun to use high strength steel belts as depicted in figure 3. These belts are comprised of hundred of steel elements attached to two bands made of high alloy steel. These belts are suitable for much higher torque applications.

Figure 3. A cut away image of a typical steel belt construction [3]

LITERATURE REVIEW

The continuously variable transmission was first theorized by Leonardo Di Vinci in 1490, as a way of transferring power between two rotating shafts. The 1880’s saw numerous patents filed for CVT’s in Europe, and a similar trend occurred in the United States in the 1930’s. It wasn’t until 1958 however, that the first practical CVT suitable for an automotive application was designed. That design came from Hub and Wire Van Doorne who created their own company, Van Doorne Transmissions. The company has since been acquired by Bosch, who continue to produce CVT components.

The United States saw the first production vehicle utilizing a CVT in 1989 with the Subaru Justy. Materials science was not as advanced as today, and for that reason CVT’s were limited to small engine applications. In the Subaru Justy’s case, it was powered by a 1.2 liter engine. The first examples of CVT applications in the US automotive market were typically riddled with reliability issues and were often underpowered. These first few CVT equipped cars made market acceptance of future versions with advanced materials, controls, and designs much more difficult.

Currently a great deal of research is going into reducing losses between the belt and pulley by optimizing their interface. In some specific designs the pulleys can account for approximately 50% of the losses in an overdrive condition [4]. Bosch in particular is working to optimize the pulley shape in order to better deal with the deformation that occurs. This concept is illustrated in figure 4.

Figure 4. Side view of conventional vs. optimized pulley shapes [5]

OPERATION OF THE TECHNOLOGY

From a stopped condition, the CVT will begin in a low “gear” position, as depicted in figure 5. In this position the driving pulley has a larger width, labeled A, resulting in a small affective diameter. Conversely the driven pulley has a more narrow width, labeled D, resulting in a relatively large affective diameter. This configuration will result in a high output torque, albeit at a relatively slow speed.
As the vehicle accelerates the mobile half of the driving pulley will slide inward along the shaft, increasing its diameter as necessary. This movement is controlled via computer. Because the belt in use is of a finite length the driven pulley will be forced to move the mobile sheave outward, thereby decreasing the effective diameter. This situation will continue until the transmission is in an overdrive state, as shown in figure 6.

**Figure 5.** CVT pulleys in a low “gear” position [6]

**Figure 6.** CVT pulleys in an overdrive “gear” position [6]

**THEORY OF THE TECHNOLOGY**

The first thing to note regarding this transmission is that both pulleys are connected via a belt of finite length. For the following explanation it is necessary to assume that this belt does not slip, and is of a finite length. Knowing this about the belt, the two pulleys will be required to have equal tangential velocities. From this point, the following correlation (equation 1) can be made between the two pulleys with regard to their individual rotational speeds and radii. This is key to the computerized balancing that occurs between the pulley radii.

\[
r_m \omega_m = r_s \omega_s
\]  

(1)

As the transmission ratio changes with respect to time, equation 2 can be used to solve for the acceleration of the driveshaft. [7]

\[
\alpha_o = \frac{-RI_e \omega_e + T_e R_e - T_i - T_d}{I_e R_e^2 + I_o}
\]  

(2)

**DISCUSSION**

As a whole the CVT appears to be ripe for growth worldwide. I think that in many markets where average vehicle size is substantially smaller than in the US, such as China and Japan, the CVT production as well as innovation will grow rapidly. In the US however, I believe this technology will continue to grow, but remain in cars that are meant to be small and efficient. Dual clutch transmissions will undoubtedly give the CVT a run for its money as the main transmission type in the US. Additionally the push towards smaller, more efficient cars should certainly help sway automotive manufacturers into at least entertaining the idea of using continuously variable transmissions. GM in particular is reportedly contemplating using CVTs in their smaller vehicles like the Cruze, Spark, and Aveo. [8] European markets seem to have trouble accepting the CVT in favor of the dual clutch transmission and other forms of an automated manual transmission. Growth in this region will more than likely be extremely slow, at least in the decade or two to come.

**CONCLUSIONS AND RECOMMENDATIONS**

I think that as far as continuously variable transmissions are concerned, they definitely have a place in modern vehicle design. There is elegance in the design, and as it continues to prove reliable and efficient, it can only get better. Comparatively speaking this technology hasn’t been at the forefront of automotive transmission technology for very long. When one considers the great strides that have taken place in the design of newer and more efficient manual and automatic transmission types over the years they have been the standards, it seems logical that the same will occur with the CVT. Currently the most pressing topic for research should be, and is the deformation

Copyright © 2011 Rochester Institute of Technology
issue. If the geometries of the pulleys and belt elements can be optimized so that losses are further reduced at high vehicle speeds, than the CVT will hold a lasting place in passenger car transmission technology. At the moment belt strength seems to be satisfactory for nearly all applications. I don’t particularly see CVTs being a major player in designs requiring even more strength. For that reason I think that the normal advances in materials science will more than likely progress faster than the markets desire for CVTs in say, full size pick up trucks.

On a personal level I am quite torn on the idea of owning a car with a CVT myself. As an engineer I love the simplicity of the concept, and clearly see the benefits in fuel economy, comfort, and acceleration. On the other hand, as a driver I have serious doubts about the feel and driver involvement with a system like this.

REFERENCES
THEORY AND OPERATION OF POWERTRAINS FOR NATURAL GAS COMPRESSORS

Donald Leclerc
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

Natural gas, and more specifically the alternative fuel compressed natural gas, holds an expanding position in the energy market. As a domestically obtained, low pollutant fuel, it has great potential for growth provided it can be as easily obtained as its competition fuels: gasoline and diesel. Natural gas is only considered an alternative fuel in its compressed state, however, and therefore the viability of the fuel in the marketplace depends on the equipment required to convert natural gas into its compressed state [2].

The purpose of this paper is to analyze the requirements of a powertrain for a CNG compressor and the possible configurations. Then it will be determined the simplest and most reliable configuration.

A system built with an Ariel Corporation CNG compressor and a Baldor explosion-proof AC motor will be efficient and reliable in its simplicity. This system features an engine and compressor that are speed matched, eliminating many potential system components. It is also a system that is capable of providing CNG in a form that is directly transferrable automobile onboard storage systems.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHP</td>
<td>Brake Horespower – Measurement of engine power without drivetrain losses.</td>
<td>(bhp)</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
<td>-</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Gas</td>
<td>-</td>
</tr>
<tr>
<td>PSI</td>
<td>Measure of pressure: pounds per square inch</td>
<td>(psi)</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
<td>(rpm)</td>
</tr>
<tr>
<td>n_r</td>
<td>Rotational Speed</td>
<td>(rpm)</td>
</tr>
<tr>
<td>P_kW</td>
<td>Power</td>
<td>(kW)</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz – measure of frequency = 1/Period</td>
<td>(Hz)</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
<td>(N m)</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatt – measure of energy = 1000 Watts</td>
<td>(kW)</td>
</tr>
</tbody>
</table>

Background

Natural gas is “mixture of hydrocarbons, predominantly methane (CH₄)” and in compressed form or liquid state it is classified as an alternative fuel by the U.S. Department of Energy according to the Energy Policy Act of 1992 [3,4]. Compressed natural gas, hereafter referred to by the trade name CNG, is valued for its “clean-burning qualities, its domestic resource base, and its commercial availability” [5].

Any alternative fuel in the United States must compete with the gasoline and diesel fuel standard. The speed and ease of these standard fuel fills at refueling stations is difficult to match, and remains a significant barrier that holds back alternative fuels like battery-stored electricity. While the infrastructure and availability of natural gas in the United States is immense, natural gas is only useful in a compressed state for transportation.

Compared to gasoline or diesel fuel, natural gas poses storage challenges, as it must be compressed in order to reach a viable energy density for use as a fuel for transportation. At pressures up to 3,600psi, CNG is stored on vehicles in high-pressure tanks [6].

A CNG refueling station’s key piece of capital is its compressor system. The speed of refueling a vehicle with a CNG tank depends directly on the flow rate of the compressed gas. A high pressure, high flow rate compressor is required for efficient refueling stations. The performance of a refueling station, and reputation and success of CNG as a viable alternative fuel depend on the efficiency of compressor systems. Some of the main factors that must be considered in selecting a compressor and matching it with a powertrain are:

- Compatibility of operating specifications and operating conditions between
- Individual efficiencies and total system efficiency
- Fuel consumption and other operating costs
- Initial Costs
- Reliability
DESCRIPTION OF THE TECHNOLOGY

Figure 1. Schematic of basic compressor system layout. Pictured with electric motor configuration.

The compressor unit in a typical quality natural gas compressor system is a unit such as the Ariel Corporation JGQ/2-1-3/4M-FS CNG model, labeled compressor in ‘Figure 1’. This model was chosen for use in this analysis due to its high 3500psi output, not requiring a multiple stage compression system, and its high quality. “Ariel’s CNG compressors are derived from the same designs that are used in field gas, process, and transmission services, intended to run 24 hours a day, 365 days a year. This experience makes the Ariel compressor one of the most robust, continuous duty rated compressors in the CNG market” [7]. With this consideration, the intent and result is removal of compressor reliability from analysis, as it can be considered perfect.

Connected to the compressor, as shown in figure 1, is a driveshaft. The driveshaft is a hollow steel tube of sufficient wall thickness to resist twisting under torque being delivered to the compressor. The compressor system contains zero, one, or two driveshafts. The system will require driveshafts if the engine or motor cannot bolt directly to the compressor and/or transmission.

Compressor systems can utilize a variety of common engines or motors to provide power. Common options include:
- Diesel internal-combustion engines
- Natural gas internal-combustion engines
- AC electric motors

Selection of a proper engine for the given compressor and other operating conditions is the main consideration of a powertrain analysis. For example, the following three different power sources each meet the power and rotational speed requirements of the compressor:
- Caterpillar/Perkins 1306C-E87TAG3 diesel engine 220kW @ 1800 rpm [8]
- Cummins GTA855E, CNG engine 191kW @ 1800 rpm [9]
- Baldor M74304T-4, Explosion-proof AC Motor 220kW @ 1785 rpm [10]

Since the rotational speed requirement of the compressor is met, no transmission is required to change the rotational speed.

The relatively small power requirement for a CNG compressor sized for a commercial refueling station allows the variety of engines and motors to be viable choices. The system would need to be supplied with a diesel fuel for the diesel engine and high voltage electricity for the AC motor. The Cummins CNG engine runs off of the same uncompressed natural gas source that feeds the intake of the compressor.

Special considerations must be made when selecting the engine or motor to power the system. Although the compressor and associated natural gas plumbing are in theory free of leaks, it is necessary to safeguard against the disastrous consequences of a potential leak. Explosion-proof electric motors, designed to operate in combustible conditions, are easy to find and specify. The internal combustion engines must be integrated into the compressor system such that no sparks or exhaust flames can interact with the potentially flammable atmosphere surrounding the compressor.

For this analysis, the issue of reliability of electricity supply is not considered. While relevant in lesser developed countries or remote areas, it is to be assumed that reliable electricity is available to supply this system. As such, the electric motor option will be analyzed further due to its increased efficiency with regards to the start-stop nature of demand at a refueling station.

LITERATURE REVIEW

Natural gas compressors are not a new technology in their own right. Their usage for CNG as an alternative fuel for dispensing to automobiles at a gas station, however, is more recent.

Electric motors as the source of power for CNG compressors “has become more common in the natural gas industry” in recent years due to increased efficiency and technology [11]. As such there has been a number of papers written as guidelines for electric motor applications, such as “Application Guideline for Electric Motor Drive Equipment for Natural Gas Compressors” sponsored by the Gas Machinery Research Council. Papers such as this cover entire system component analysis for design considerations that do not concern typical internal combustion engine powerplants.

Literature on reengineering currently existing compressor systems and updating/upgrading them with newer, more efficient, and more powerful electric motors is also of value. These papers are published by major manufacturers such as Siemens, which sponsored the paper “Revamping a Gas Compressor Drive Train From 7000 to 8000 HP With a New Synchronous Motor Driver and a Controlled Slip Clutch Mechanism”[12]. Along similar lines to the
‘Application Guidelines’ papers, these revamp studies cover special considerations that must be made for high-horsepower electric motors that don’t apply to internal combustion engines, such as torque variations due to variations in supplied electricity.

OPERATION OF THE TECHNOLOGY

The operation of the powertrain for this simple and reliable natural gas compressor takes an input of constant 50Hz AC voltage and outputs torque on the crankshaft of the compressor frame.

460VAC at 60Hz with a “combined variation in voltage and frequency of ±10% (sum of absolute values) of rated values provided the frequency variation does not exceed ±5% of rated frequency” must be supplied to the Baldor M74304T-4, Explosion-proof AC Motor. This asynchronous induction motor generates a torque on the central rotor through the interaction of a rotating magnetic field and induced rotor current [13]. This continuous duty rated motor requires no variable speed controlling, since it operates at a speed of 1785rpm, which is within the standard operation speed of the compressor in the system.

The torque on the central rotor is output through a coupling that is mechanically attached, bolted or keyed, to the input shaft of the compressor. The coupling between the motor’s output shaft and the input shaft of the compressor frame should be a flexible type in order to limit mechanical vibration generation due to potential misalignment and limit mechanical vibration transmission from another source [14]. The torque transmitted through the spinning driveshaft should be the only force transmitted between the motor and compressor, in either direction. The two must be mounted such that no axial forces are present i.e. the weight of the compressor imposing on the driveshaft with an axial component. The electric motor bearings are not built to accommodate thrust loading and can fail when loaded improperly [15].

The matching of the specified speed of the AC motor with the requirement of the compressor allows torque to be transmitted directly between the two without a change in shaft speed by way of gearbox or a belt and different sized pulleys. The matching of the specified power or the AC motor with the requirement of the compressor also allows direct torque transmission without the requiring a slip clutch. A slip clutch is designed to provide protection for the compressor from torque surges from the motor to the compressor due to variations in input electricity into the motor [16]. Provided that CNG accumulation tank is sized to provide a large enough buffer for the compressor to refill the tank without undue load from customers demanding CNG fueling, the compressor will not see undue loading. Operation for this system is intended to be steady-state once the motor switches on to keep the CNG accumulation tank above a desired threshold.

The input shaft to the compressor should also utilize a flexible coupling such that any new vibrations generated by a potentially out-of-round driveshaft or damage to the driveshaft or the motor-side coupling be isolated from the compressor. The compressor’s input shaft receives 220kW of power by way of the rotating shaft at a speed of 1785rpm [17].

This input power and speed is an ideal match for the input requirements of the Ariel Corporation JGQ/2-1-3/4M-FS CNG model [18]. The system reliability is higher due to the proper matching, since variable controllers or gearboxes and their own potential reliability issues are not involved.

THEORY OF THE TECHNOLOGY

The source of shaft power for the compressor is the 220kW asynchronous induction electric motor. The torque produced by the motor and transmitted to the driveshaft is subject to the equation:

\[
T = 9550 \frac{P_{KW}}{n_r}
\]

where

\[
T = \text{rated torque (Nm)}
\]

\[
P_{KW} = \text{rated power (kW)}
\]

\[
n_r = \text{rated rotational speed (rpm)}
\]

According to that equation, the torque output from the motor through the driveshaft is 1,177Nm.

The coupling between the electric motor’s output shaft and the driveshaft is direct with no difference ratio. Therefore the transmission can be considered 1:1. The motor and compressor are assumed to be mounted with input/output shafts aligned axially to a high degree of accuracy and therefore the flexible coupling between the driveshaft end and the motor output shaft is assumed to have negligible frictional resistance.

The driveshaft chosen must be able to resist the torsional force due to the torque applied. Design considerations must include the shear stress of the material and the maximum torque in order to find an appropriate driveshaft. There are driveshafts in the marketplace that combine the shaft itself along with flexible couplings on either end to join the motor and compressor. A unit like the R&W Coupling Technology Line Shaft Model ZA with conical sleeves has a limit of 1500Nm and utilizes flexible couplings to account for misalignment. A product like this is zero maintenance and has an infinite life within design limits, effectively eliminating it from consideration with respect to reliability. [20]

DISCUSSION

The future is bright for alternative fuels and the hardware that supports their infrastructure. Compressed Natural Gas in particular benefits from an...
Compressed natural gas as an alternative fuel for transportation is an emerging technology with growing trends in its favor, including “tighter emissions controls on cars and trucks; concern about reliance on foreign oil; and large domestic reserves of natural gas” [xxiii]. The technology has room to improve as well, with research and development on increasing fuel efficiency and designing specific engines intended to use CNG, rather than retrofits. With the support of a strong distribution infrastructure built on reliable and efficient compressor-driven CNG refueling stations, the market share of the technology is sure to grow.

The CNG market, with the integral compressor system to deliver the product to the user’s vehicle in a usable compressed state, has the potential to be a largely domestic enterprise. Large natural gas reserves inside of US borders could allow money normally sent overseas oil producing countries to be spent on US natural gas instead and aid the economy [23].

CONCLUSIONS AND RECOMMENDATIONS

I believe that compressed natural gas, as a technology, has a bright future. With its already huge commercial availability for home heating and appliance use, as opposed to hydrogen or similar, it features fewer hurdles before commercial success. One of the hurdles, conversion from NG to CNG is accomplished with a natural gas compressor. These technologies must go hand-in-hand for CNG as an alternative fuel to be successful.

The importance of reputation for a product cannot be overlooked. If CNG develops a bad reputation with the public, many buyers may be discouraged from buying CNG cars or conversions for their IC engines. Reliability of distribution, therefore, is key. With reliable compressors working at refueling stations, the chances for down-time and inconvenience to customers is greatly reduced. CNG refueling must be at least as easy as gas/diesel refueling in order for it to be truly successful. Reliable compressors supplying reliable refueling will help this.

I believe that simplifying a system by removing unneeded components will improve reliability. With the variety of reliable Ariel compressors made to match virtually any of the commonly available motors/engines, a direct drive system with no variable drive is easily configured. Parts count is extremely low, with each part being little to know maintenance.

Simple and reliable CNG compressor systems have the potential to be a huge market to support the growth of CNG as an alternative fuel. They could easily be a standard unit in this configuration in almost any refueling station.

REFERENCES


Copyright © 2011 Rochester Institute of Technology
THEORY AND OPERATION OF A CVT APPLICATION IN AN 
INDUSTRIAL LATHE HEADSTOCK

Alan Mattice
Mechanical Engineering Student
Rochester Institute of Technology

Abstract
This paper describes the functionality of 2 existing technologies, Constantly Variable Transmissions (CVT) and Industrial lathe headstocks. Furthermore, it examines the potential for the use of a CVT in a lathe headstock. Industrial lathes are used in a wide variety of industries and are a tried and proven backbone in the manufacturing industry. CVTs are a relatively new and developing technology, largely driven by the automotive industry. Traditionally lathe headstocks were driven by sets of gears to achieve a number of gear ratios. CVT Transmissions offer advantages over normal gearing, and would prove to be a very good fit in a lathe headstock.

Background
Industrial lathes are critical to our manufacturing industry. Large industrial lathes are commonly used to make rolls for steel mills, turbine shafts, generator shafts, train wheels and axles, and ship shafts. This paper focuses on machines typically driven by a 100 – 300 HP electric motor. Historically large industrial lathes have had multiple gears, enabling them to run at a wide variety of speeds. The problem here is that adding gears to a headstock adds cost, and decreases efficiency. Also, even with the ability to run in multiple gears, the lathe must be stopped to change gears, making it difficult to turn surfaces of various diameters continuously. Modern motors and controls have partially alleviated this problem by offering a wider range of motor speeds, but the range where the motor can run efficiently produce it’s full rated horsepower is still limited. Also, in applications where various diameters are being machined in a single cut, the lathe speed must change in order to keep a constant surface speed at the cutting tool. This can be very hard to do when the lathe you have is limited to certain RPM ranges in each of it’s gears. The ability to change the ratio between the motor and the part would prove very valuable here.

Attempts have been made to mimic the functionality of a CVT. For example, Some Binns’ Super-lathes use a motor-generator set to generate power, to turn another electric motor, which drives the machine spindle. This works much like a diesel-electric train engine, except that the beginning of the powertrain is an electric motor rather than a diesel engine.

CVT transmissions have primarily been seen as something for the automotive industry, but as they become better developed, and more robust, it is only logical that they will begin to show up more in other applications. In 1987 Subaru became the first automobile manufacturer to offer a CVT transmission in a production vehicle. Today most major vehicle manufacturers offer at least some models with CVT’s as standard equipment. The advantages over traditional transmissions are clear. Better fuel economy, smoother operation, and in some cases better performance than a normal 5 or 6 speed transmission are all big selling points.

Many gearbox manufacturers are already making variable speed “gearboxes” based on CVT technology. As CVT’s become better developed and more cost effective it is expected that they will be more widely accepted in industry. So far, I have not found any large lathe applications of CVT’s. It seems like a logical fit, and therefore I assume it is something that other lathe manufacturers have looked into, and are possibly working on.

Of the various types of CVTs in existence, the most promising for a lathe looks like Toroidal designs or Hydrostatic designs. Both of these will be described in detail in later sections of this paper.

Description of the Technology
A lathe headstock is essentially a large gearbox. The headstock has 3 primary functions. To rotate the work piece, support the work piece radially against gravity and radial machining forces, and to support the workpiece axially against the tailstock and axial machining forces.

In order to support the work piece radially, a large front bearing is used. This front bearing is also responsible for the accuracy of the machine.

To support the work piece axially a large thrust bearing is typically used. This thrust bearing can be
located behind the front spindle bearing, or farther back, towards the rear of the headstock.

In order to rotate the workpiece a series of gears, is implemented to transfer torque from the motor to work piece. Typically at least 2 gears can be shifted, resulting in 4 or more overall ratios. See figure 1 and 2 below for a gear layout of a typical lathe headstock. In this case the machine is a 250 HP lathe.

![Figure 2. Photograph of headstock with cover removed, from a Macintosh Hemphill Lathe. [9]](image)

Although the headstock is the focus of this paper it is only a portion of the entire machine. As a system the machine typically needs to be able to run multiple axes in coordination. For example to cut threads on a workpiece the machine would need to run the headstock at a specific RPM, and feed the carriage at a specific speed. In order to cut a second pass on the same threads the machine also needs to know the indexed position of the faceplate. For operations such as this a low backlash drive train is needed.

Because the headstock needs to work synchronously with other parts of the machine, the headstock drive can not slip. For this reason it is common for headstock drive motors to drive a timing chain or be directly geared into the headstock. V-belts, and other friction based drive mechanisms are avoided.

A lathe equipped with a CVT would perform in much the same manor as a lathe equipped with traditional gearing. A headstock drive motor would turn an input shaft on the gearbox. From there a CVT would be used to vary the speed over as much a range as possible. The output of the CVT ideally would be as low a speed as the CVT is capable of transmitting the full motor horsepower. After the CVT, a series of speed reduction gears would be used to lower the speed to the desired speed at the machine spindle. In most cases headstock gearing consists of double helical or herringbone gears. This would still be the case in the gearing used after the CVT in the lathe power train.

CVTs come in a wide variety of types, each type having advantages and disadvantages over the others. For reasons discussed in later sections, the best fit for a lathe headstock drive seems to be a toroidal design or a hydrostatic design.

Toroidal CVTs use a set of wheels facing each other with a sphere between them. This sphere contacts both wheels at a point. If the axis of the sphere is perpendicular to the axis of the wheels, the contact point on each wheel is on the same radius and the ratio is 1:1. If instead of using flat wheels, wheels that are dished are used, the sphere can be tilted to change the contact point’s radius, and in turn change the transmission ratio. [5,7] This design can be seen in figure 4 below.

![Figure 3. Toroidal CVT concept sketch.][1]

A toroidal design would be a good fit because they are relatively efficient, can run at high speeds, and can offer a good range of ratios. The toroidal CVT would be located near the input end of the headstock, in order to minimize the torque requirements on it. The downside to this design is that it is a friction drive, and some slipping is possible.

A Hydrostatic design seems to be the best fit. The downside being that it would involve a drastic re-design of the headstock. The hydrostatic drive is not a friction drive, but still can have losses that would appear as slip. The hydrostatic design would involve a motor driven variable displacement hydraulic pump, which would supply hydraulic fluid to a hydraulic motor. This hydraulic motor would...
them be used to drive the headstock gearing. This would involve few moving parts, and would be a robust design. Figure 5 shows the operating concept for a hydrostatic drive. A pump is driven by the input shaft, which then creates hydraulic pressure and flow, which is then used to drive a hydraulic motor. The speed can be varied by using a variable displacement hydraulic pump. This action of changing the pump displacement is effectively changing the gear ratio of the system.

![Figure 5: Hydrostatic Drive Concept Schematic](image)

Implementing a hydrostatic drive system in a lathe would be a large leap from a traditional design. The drive motor would be replace by a simple AC motor and pump. Much of the gearing would be eliminated, and the overall size of the headstock could be reduced. However, the hydrostatic design would generate a lot of heat.

**Literature Review.**

The idea of an infinitely variable transmission is nothing new. Leonardo DaVinci is typically credited as having the original concept. In 1490 DaVinci drew his concept for the CVT Transmission, shown below in figure 6.

![Figure 6. DaVinci's Concept sketch of a CVT](image)

In 1877 Charles W Hunt Filed a Patent application for what is basically a toroidal CVT as we know it today.[3] Hunt is typically credited with the invention of the toroidal CVT. See Figure 7 for Hunt’s Drawings.

Since Hunt filed His Patent GM developed a Toroidal Transmission in the 1960’s, but decided it was less practical than having set gear ratios.

Hydrostatic transmissions have been developed by many companies for different industries. [4] Today they are mainly used in driving agricultural and construction equipment. It is rare to find a Hydrostatic transmission in a over-the-road vehicle due to the viscous losses in the transmission at high speeds.

![Figure 7. Drawings submitted with US Patent# 197,472 by Charles W. Hunt.](image)

As for the other half of the Technology in this paper: Lathes date back to ancient Rome, Greece and Egypt. They saw major revisions during the Industrial revolutions of the UK and the United States, and eventually developed into the lathes we know today. [6] In the large scale section of the industry, there have not been many large revisions to a typical lathe since the 1950’s. Manufacturing methods in producing the machine, as well as the manufacturing that the machine is intended to do have changed however. This has been the primary drivers for recent work in this area.

Today there are less and less companies producing large scale machine tools. There are even fewer companies with large scale capacities in this country. Machine Tool Research, in Rochester, NY is one company still producing and servicing large scale
lathes. If a CVT were to be applied to an industrial lathe there is a good chance MTR would develop the technology, and adapt the CVT into a headstock design.

Other companies that could have an interest in development of a CVT driven lathe could include Waldrich Siegen (Germany), Tacchi (Italy), or Skoda (Czech Republic).

**Operation of the technology.**

A large industrial lathe typically has a drive motor above the headstock, or behind the headstock. The motor usually drives the headstock with a synchronous belt or a drive chain.

![Figure 8. Drive Belt connecting motor to Headstock input shaft. (un-tensioned)](image)

Inside the headstock gearing is used to reduce the shaft speed and increase the shaft torque. A typical headstock will have at least 3 shafts. This allows for multiple gear ratios that can be used to turn the part. General speed ranges are from 2-200 RPM. Most lathes will cover this range with at least 4 gear ratios. Some will have 10 or more gear changes in order to cover the RPM Range. A typical speed range chart is shown in the following figure.

![Figure 9. Typical lathe Speed Range Chart](image)

Typically lathes of this size use double helical gearing. This eliminates the axial loads on the input and intermediate shafts. Shafts are generally supported by tapered roller bearings. The spindle is responsible for supporting the chuck, and in turn the work piece. The spindle is typically supported by a large tapered roller bearing or a cylindrical roller bearing and a large thrust bearing. The figure below is a drawing of the headstock shown in figure 1. This machine uses all double row tapered roller bearings and double helical gearing.

![Figure 10. Macintosh Hemphill Lathe Gearing Layout (reference photo in figure 1)](image)

The final part of the headstock is the faceplate or chuck. The chuck is the part of the headstock that holds the work piece and rotates the work piece. The chuck must transmit the torque from the headstock to the work piece.

A headstock also requires an auxiliary lubrication system to provide a stream of oil to each gear mesh and to each bearing or bushing. The example shown in figures 1 and 8 includes two independent lubrication systems. One is a low pressure, high flow system for the gear meshes and bearings. The second is a high pressure system for the bushings between the change gears and the intermediate shafts. If a CVT was used in place of the change gears, one of the lubrications systems could be eliminated all together, and the second lubrication system could be a lot smaller.

If a Lathe were developed with a toroidal CVT, the headstock would likely be modified as follows. The drive motor and belt or chain would be retained. The input shaft of the headstock would be the input shaft of the toroidal drive, the toroidal drive would increase, or decrease the shaft speed as appropriate. The output of the toroidal drive would then turn an intermediate shaft equipped with a pinion that would turn the gear on the spindle. Depending on the application another gear reduction may be needed in...
order to get the speed reduction and torque required. This system would be a relatively easy transition from a regular design.

If a hydrostatic CVT were to be implemented a more radical change would be required. In the application of a hydrostatic drive to a lathe headstock it is likely that the belt or chain driving the input shaft of the headstock would be eliminated. The motor would run a variable displacement hydraulic pump at a constant RPM. This would result in a much simpler control system for the machine. The pump displacement would be varied by a servo controlled mechanism. The pump could then be plumbed to a hydraulic motor, which would directly turn a pinion mating with a gear on the machine spindle. This system would be simple and robust. The downfalls here include the expense of a full horsepower hydraulic pump and hydraulic motor, and the heat generated in the hydraulic system. The system would likely require an external oil cooler to help dissipate heat from the hydraulic fluid.

Conclusions and Recommendations

A lathe headstock is essentially the same as a manual transmission in a car, but on a larger scale. CVT’s are becoming a proven technology in automotive applications, but have not yet emerged in the machine tool industry.

Continuously variable speed lathes are currently available, but only in the form of small tool room lathes. Generally these machines are not a true CVT, but are equipped with a widely variable speed motor. Even these variable speed lathes do however usually have a high and low speed range, which could be eliminated with a true CVT.

Adapting a CVT into an existing machine does not seem like a practical idea. Too much design change would be required to make it cost effective to convert an existing headstock to a variable speed design.

Having a CVT in a lathe headstock would give better performance (as far as material removal / hour) , because the motor could run in a full HP range more of the time. The CVT would also allow the machine to make constant surface speed cuts on tapered surfaces, or during facing operations where with a conventional machine the cut would have to be interrupted to shift the headstock out of one gear and into another.

Along with better performance, A CVT in a lathe headstock has the potential to offer better efficiency and less moving parts in the headstock.

I think it is only a matter of time before someone designs and builds a large industrial lathe equipped with a CVT.

References

Toroidal Figure: <http://www.excelermatic.com/pages/figure3.htm>
Toroidal Figure: <http://www.jsme.or.jp/English/awardsn20.htm>

Acknowledgments:

BICYCLE POWER TRAIN

Zachary J. Miller
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

A bicycle power train is a mechanism that transmits power from the rider to the drive wheel [1]. There are a variety of different mechanical components that make up a successful power train. Each component performs a specific function that is needed to make the power train work. It is not only important that a bicycle power train work, but also that it be efficient. An inefficient power train gives less output (speed / distance) for a given amount of input (human energy). A good power train, such as the one found on a Cannondale® R800, will allow for an efficient transfer of power from the rider to the drive wheel. In order to achieve a state of efficient power transfer, one must understand the science of a bicycle power train. A bicycle power train is governed by a variety of scientific principles. Studying these principles makes it obvious that a properly designed bicycle power train allows for a very efficient power transfer. This efficient power transfer, coupled with the fact that it is human powered, makes the bicycle an excellent mode of transportation. With the increasingly high gas prices and the growing concern about global warming, the future of the bicycle looks bright.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>Cadence</td>
<td>rpm</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
<td>W</td>
</tr>
<tr>
<td>A</td>
<td>Frontal Area</td>
<td>m²</td>
</tr>
<tr>
<td>V</td>
<td>Velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>S</td>
<td>Slope</td>
<td>rise/run</td>
</tr>
<tr>
<td>CL</td>
<td>Crank Length</td>
<td>mm</td>
</tr>
<tr>
<td>Eff</td>
<td>Effective Pedaling Range</td>
<td>deg</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
<td>N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subscripts and Symbols</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>av</td>
<td>average</td>
</tr>
<tr>
<td>eff</td>
<td>effective</td>
</tr>
<tr>
<td>w</td>
<td>wind / drag</td>
</tr>
<tr>
<td>rr</td>
<td>rolling resistance</td>
</tr>
<tr>
<td>p</td>
<td>pedal</td>
</tr>
<tr>
<td>C</td>
<td>Coefficient</td>
</tr>
<tr>
<td>FT</td>
<td>No. of Front Chainring Teeth</td>
</tr>
<tr>
<td>RT</td>
<td>No. of Rear Chainring Teeth</td>
</tr>
<tr>
<td>ro</td>
<td>Roll Out</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>R</td>
<td>Ratio</td>
</tr>
<tr>
<td>G</td>
<td>Gear</td>
</tr>
<tr>
<td>g</td>
<td>Gravity</td>
</tr>
</tbody>
</table>

BACKGROUND

Bicycles in today’s world have a variety of applications. They are used for many different activities, including exercise, entertainment, racing, and even transportation. Power train technology is especially important for bicycle racing and transportation. Over the past few years, bicycles have become a very attractive form of transportation. This is due to rising gas prices and the growing concern about pollution / global warming.

NASA [2] has reported that arctic sea ice has been decreasing by 11.5% per decade while carbon dioxide and sea levels have risen 390 parts per million and 3.27 mm per year respectively. NASA [2] also claims that the average global temperature has raised 1.5ºF since 1880 and that the amount of land ice in Greenland has been decreasing at a rate of 24 cubic miles/year. Reports such as these have generated a great deal of concern about global warming and the effects that humans are having on the planet. In addition to environmental concerns, people have also been experience a great deal of economic struggles.

In an article about rising gas prices, CNNMoney [3] expressed that, “Over the last year, prices are up 39 cents a gallon or 14%”. Economic struggles, coupled with rising gas prices have encouraged people to find less expensive modes of transportation. As a result, many people are finding the bicycle to be a cheap
alternative to the automobile. Not only is cycling cheaper, but it is also emissions free. This helps to combat the previously mentioned environmental issues.

In order for a bicycle to succeed in the transportation world, it must satisfy the needs of the rider. The primary goal of bicycle commuting is to comfortably get from point A to point B without expending too much energy. Thus, it is important that bicycles allow for an efficient transfer of power from the rider to the drive wheel. This task is accomplished by the bicycle’s power train.

Although power transfer is an important part of commuting, it is even more important for racing. In an article entitled “The Physiological Effects of Endurance Events”, Lynn Thompson [4] states that, “For all endurance athletes, the critical determinant of success is their ability to sustain a high rate of energy output for extended periods of time”. Although top-notch endurance athletes are very good at sustaining high rates of energy, they cannot afford to be wasting such precious energy. This is wear the power train becomes very important. An efficient power train will transfer as much energy as possible from the rider to the drive wheel. An inefficient power train will waste a great deal of the rider’s energy through things such as frictional losses. Thus, it is theoretically possible for a cyclist to lose a race, not because he was less fit, but because his bicycle’s power train was less efficient than that of his competitor.

Fortunately for cyclists, power train systems are not a new technology. Bicycle power trains have been around for a very long time. As a result, designers and engineers have made power train design a rather mature technology. Today’s bicycles use a variety of different types of power trains. As time passes the power trains become more and more efficient. This leads to faster commutes and more enjoyable rides. The Cannondale R800 is an excellent example of a bicycle power train that has achieved such things.

DESCRIPTION OF THE TECHNOLOGY

Bicycle power trains are not overly complicated mechanisms. While there function is very important, their make up is much simpler than that of a car or some other type of machinery. There are various different types of power train systems. This paper will focus on the type of power train found in a Cannondale® R800 road bike. Figure 1 shows a bicycle power train similar to that of a Cannondale® R800.

![Figure 1](image1.png)  

**Figure 1.** shows a power train similar to that of a Cannondale® R800. Adapted from [5].

Referring to FIG. 1, the Cannondale® R800 power train is comprised of two control cables 1, a crank with two chain wheels 2, two shifters 3, two pedals 4, a front derailleur 5, a rear derailleur 6 (with jockey rollers), a chain 7, a free wheel 8 with 9 cogs, and a bottom bracket axle 9. Figure 2 shows a detailed view of the Shimano 105 dual control levers (shifters), which are attached to the handlebars.

![Figure 2](image2.png)  

**Figure 2.** shows an exploded view of the Shimano 105 Dual Control Levers. Adapted from [6].

Referring to FIG. 2, the dual control levers have a right and left hand main lever assembly 1, each of which contains a front cover unit 2. The front cover units each have two name plates with fixing screws 3, 4 and a front cover fixing screw with a toothed washer 5. Between the main levers 1 and the brackets 16 there is a right hand adapter spacer 6, a left hand rear cover 7, another left and right hand adapter spacer 8, a lever axle bush unit 9, a non turn washer 10, a lock nut 11, and a cable hook unit 12. Surrounding/connected to the brackets 16 are right and left hand return springs 13, a clamp band unit 14, a clamp nut and washer 15, four right and left hand adjustment blocks 17, a lever axle fixing screw 19, right and left hand water-proof cap and fixing screws 20, a pair of bracket covers 21, an outer cable guide 22, and an outer cable joint 23. All of the plates and spacers are connected by the fasteners to form the dual control lever assembly. A cable runs over the cable guide 22 in the left hand control lever, along the bottom of the down tube and connects to the front derailleur. **Figure 3 shows a**
detailed view of the Shimano Tiagra 9-speed front derailleur.

**Figure 3.** shows an exploded view of the Shimano Tiagra 9-speed front derailleur. Adapted from [6].

Referring to FIG. 3, the front derailleur attaches to the seat tube via the clamp band unit 8, which is comprised of a clamp bolt 11, a clamp spacer 12, and another clamp bolt 10. The clamp bolt 11, along with the clamp spacer 12, clamps the band unit 8 to the chain guide FD-4403. The chain guide FD-4403 is comprised of stroke adjust screws 3, a chain guide fixing screw 4, and a cable fixing bolt unit 4. The clamp bolt 10 clamps the entire assembly around the seat tube.

The second derailleur cable runs along the bottom of the bicycle frame from the right control lever to the rear derailleur. Figure 4 shows a detailed view of the Shimano 105 RD-5501 9-speed rear derailleur.

**Figure 4.** shows an exploded view of the Shimano 105 RD-5501 rear derailleur. Adapted from [6].

Referring to FIG. 4, the gear fixing bolts fasten the chainring 50T 12 and the chainring 34T 11 to the right and left sides of the right hand crank respectively. The ring 5 slides onto the shaft of the right hand crank, which passes through the bottom of the bike frame, the right hand adapter 9, an O-ring 8, the inner cover 7, another O-ring 8, the left hand adapter 6, another ring 5, the 172.5 mm left hand crank arm 2, and connects to the crank arm fixing bolt 1. The clamp bolts, washers 3 and plate 4 clamp the left hand crank arm 2 to the shaft of the right hand crank arm. Attached to the left and right hand crank arms are a set of pedals. Figure 5 shows a detailed view Shimano 105 SPD-SL pedals.

**Figure 5.** shows an exploded view of a set of Shimano 105 SD-SL pedals that could be attached to the crank arms. Adapted from [6].

Referring to FIG. 5, the pedal axle assembly 1 is comprised of a shaft which screws into the threaded hole in the crank arm and passes through the lock bolt 2 and steel balls 3, attaching to the base of the pedal. The binding pin passes through the base of the pedal, through the binding 6, and into the spring cover 10. An indicator 7 is attached to the binding 6 through the inner plate 13 and the guide pulley unit 11, connecting to the outer plate assembly 9 on the other side.
and a body cover 4 can be attached to the base of the pedal. The spring cover 10 houses the two springs 13 which are held in place by the spring adjustment bolt 8, the adjust e-ring 9, the adjust plate cover 11, and the adjust plate 12. Each pedal has a corresponding cleat set 14 that is fastened to the bottom of the cyclist’s shoe via the cleat washer 16 and cleat fixing bolt 15.

Attached to the rear wheel are a set of 9-Speed cassette sprockets. Figure 6 shows a detailed view of the cassette sprockets.

![Figure 6](image)

**Figure 6.** shows an exploded view of the 9-Speed 12T-26T Cassette Sprockets. Adapted from [6].

Referring to FIG. 6, the sprockets are fastened to the rear wheel in the order shown above. The sprocket unit (21T-23T-26T) 11 is fastened closest to the center of the wheel, followed by another sprocket unit (17T-19T) 10, followed by a sprocket spacer 14, followed by sprocket wheel 15T 9, followed by another sprocket spacer 14, followed by sprocket wheel 14T 8, followed by another sprocket spacer 14, followed by sprocket wheel 13T 7, followed by sprocket wheel 12T 4, followed by a lock ring spacer 2, followed by a lock ring 1. The lock ring fastens to the end and prevents the sprockets from sliding off the shaft. The entire sprocket assembly attaches to the rear wheel shown in figure 7.

![Figure 7](image)

**Figure 7.** shows an exploded view of the rear wheel and free hub. Adapted from [6].

Referring to FIG. 6, the complete hub axle 3 is made up of a hub axle 8 that passes through the hub, the steel balls 7, and the lock nut unit, which includes the seal rings 5 and o-rings 6. The complete hub axle is capped off on each side with a hub cap 2. A quick release 1 is fed through this entire assembly and is used to clamp the wheel into the rear fork joints. The spoke unit 10 completes the wheel. Nipples 11 at the end of each spoke connect the spokes to the hub. The spokes extend outward and attach to the rim 9.

The final piece of the Cannondale R800 powertrain is an SRAM PC 951 chain. Figure 8 shows a detailed view of a bicycle chain.

![Figure 8](image)

**Figure 8.** shows an exploded view of a bicycle chain. Adapted from [7].

Referring to FIG. 8, the bicycle chain is made up of a bearing pin 1, a bush 2, a roller 3, an inner plate 4, and an outer plate 5. The roller 3 slides over the bush 2. The bearing pin 1 then slides through the bush 2 and the inner plate. The outer plate 5 snaps onto the end of the bearing pin 1 that is protruding from the inner plate. Performing this set of connections repeatedly results in a full length bicycle chain. Some chains have a special release link for easier repair/maintenance.

**LITERATURE REVIEW**

According to Wilson [8], bicycles got their start many years ago and were much less sophisticated than they currently are. The first ever bicycle is credited to Baron Karl Von Drais, who created a two wheeled “running machine”. Von Drais’s “running machine” was called le velocipede and eventually became known as the Hobby Horse. Unfortunately, the Hobby Horse was primarily for the rich and it died out as railway travel took flight. Many years later, in 1860, the first bicycle boom occurred. Unlike the Hobby Horse of earlier years, the bicycles of the 1860’s could be pedaled. Although it is controversial as to who invented the first pedal bicycle, what is known is that such bicycles were wildly popular. By the late 1860’s bicycles were being made with rubber coated wheels and ball bearings. These types of advancements gave bicycles a smoother ride.

Wilson [8] also states that while bicycles thrived in Europe, they struggled to succeed in America. The poor quality of roads in America was one of the primary things that stunted American bicycle growth. Without good roads to ride on, the bicycle was not as useful as it was in other parts of the world. While America struggled, bicycle innovation continued in other parts of the World. Eugene Meyer developed a suspension/tension wheel in 1869, James Starley and William Hillman created a bike with radial spokes and a lever for tensioning and torque...
transmission, and James Starley also patented the tangent-tension spoking method (1874). Surprisingly, Starley’s spoking is the method that is used to this day.

Tension spoking was a very important development because it allowed the front wheel of a bicycle to be made larger. The larger the front wheel, the greater the distance I cyclist could travel with each turn of the pedals. As a result, “high-wheeler” or “ordinary” bicycles became quite popular. “High-wheels” were bicycles with a large front wheel and a much smaller rear wheel. The seat was positioned over the larger wheel which was driven by a set of pedals attached directly to the front axle. Some “high wheelers” had a drive wheel with a diameter as large as 60 inches. Although “high wheelers” could cover great distances in relatively small periods of time, they were relatively dangerous and required a fair amount of athletic ability/balance to ride. As a result, tricycles and quadricycles were developed for those who were less daring / athletic [8].

Wilson [8] also stated that a new type of bicycle, called the safety bicycle was developed in the late 1800’s. The Rover safety bicycle of 1885 was very similar to today’s current bicycles. It was a much safer design than the “high-wheeler”, featuring much smaller wheels, a chain drive, and a seat that was positioned between the rear drive wheel and the front steering wheel. Shortly after the creation of the safety bicycle, John Boyd Dunlop patented the pneumatic tire. The pneumatic tire was a very important part of bicycle history and was followed by several other advancements. Perhaps the most important advancement was the derailleur, which was developed in France and Britain in 1895. Surprisingly, the derailleur was not very popular at first and was not accepted for racing until 1920. Since that time it has become one of the most important parts of a bicycle powertrain.

Since the creation of the derailleur in 1895, bicycle powertrains have continued to improve. Although the basic concept has remained largely the same, the quality of the powertrains has greatly improved. Improvements in chains, cranks, shifters, and derailleurs have lead to smoother, easier to use, more efficient powertrains with a large number of gear selections. One significant change was moving the shifters from the down-tube to the handlebars, allowing cyclists to change gears more easily. Non-round chainwheels were powertrain advancement. The intent of such mechanisms was to reduce the amount of time that the pedals spend near the top and bottom of the pedal rotation. Unfortunately, there has been insufficient evidence to determine weather or not non-round chainwheels provide any sort of advantage. In addition to the non-round chainwheel, there have been several other unique powertrain developments. Many of them, however, stray from the traditional type of powertrain found on the Cannondale R800. Most future advancements will probably come in the form of refinements that make current designs lighter, smoother, and easier to use [8].

OPERATION OF THE TECHNOLOGY

Power transfer is a very important part of cycling. To fully understand power transfer in cycling, one must analyze the source of the power, that being the cyclist. As expressed by Wilson [8], in order to generate any sort of power a cyclist must consume some type of fuel (input). This fuel comes in the form of food and/or drink. Once the fuel is consumed muscle cells convert the fuel’s chemical potential energy into mechanical work. This allows the cyclist to generate an output in the form of muscular movements. These muscular movements are used to transmit energy to the crank-shaft (by pressing on the pedals with the foot), creating a torque in the crank. As the crank receives the input from the rider, it rotates, imparting a force from the teeth in the chain ring, to the pins in the chain. This creates a tensile force in the chain. The taught chain exerts a force on the teeth in the rear sprocket. The force on the teeth in the rear sprocket creates a torque in the wheel. The combined weight of the rider and the bicycle, along with the coefficient of friction between the tire and the road surface, will create a tractive force between the tire and the road surface. If the driving force supplied by the cyclist exceeds the tractive force, the tire will slip. If the driving force supplied by the cyclist is less than or equal to the tractive force, the tire will not slip. According to analytic cycling [9], if the tire does not slip, and the power generated by the cyclist is great enough to overcome the forces acting against the cyclist (wind resistance, rolling resistance, and gravity), the bicycle will move forward.

Once a cyclist starts moving forward, they can do one of two things to increase their speed. The first is to increase their cadence and the second is to keep their cadence the same and increase their gear ratio. Given that it is not comfortable to pedal at extremely high cadence, the logical thing to do is shift into a higher gear ratio. In order to change gears, a cyclist must adjust the shifters. The Cannondale® R800 has a set of Shimano 105 dual controllers fastened to the handlebars. Pushing the larger, silver, left-hand lever (break lever) towards the center of the bike pulls on the derailleur cable, increasing its tension. This imparts a force on the derailleur arm, causing the chain guide to pivot from the 34T chain-ring out to the 50T chain-ring. Pressing the smaller, black, left-hand paddle decreases the tension in the cable allowing the spring-loaded derailleur arm to return to its position above the 34T chain-ring. As the chain guide moves from one chain-ring to the next it guides the chain onto the desired chain-ring. The same process is used to shift the rear gears, the only difference being that the adjustments are made with the right-hand dual controller instead of the left-hand one. For the rear derailleur, increasing the tension in

Copyright © 2011 Rochester Institute of Technology
the cable imparts a force to the derailleur arm, causing it to pivot towards the center of the wheel. Doing this expands the B-tension spring located inside the B-axle assembly. When the tension is released the B-tension spring contracts and moves away from the center of the wheel (towards the 12T sprocket) [6, 10].

The chain is able to move from one sprocket/chain-ring to the next not only because of the derailleur, but also because of the design of the sprockets themselves. Careful inspection reveals that some sprocket teeth are shorter and wider than the others. These shorter, wider teeth help to grab the chain and pull it onto the sprocket. In addition, the sprockets also have “special grooves in the side that help to pull the chain onto the sprocket” [10].

### THEORY OF THE TECHNOLOGY

Bicycle power transfer begins with the source of the power, the cyclist. The cyclist consumes some sort of fuel and his muscle cells convert the fuel’s chemical potential energy into mechanical work (muscular movement). Unfortunately, humans are only about 20 to 30 percent efficient at processing fuel. Thus, 80 to 70 percent of the energy is dissipated as heat (waste) [8]. The remaining energy is used by the cyclist to push the pedals. Pushing on the pedals generates a force. The average pedaling force that is applied during each revolution is defined by Eq. (1) [9].

\[
F_{av} = \frac{P}{V_p} \tag{1}
\]

The pedal speed in Eq. (1) is defined by Eq. (2) [9].

\[
V_p = \frac{C_d \times C_L \times 2 \times \pi}{60 \times 1000} \tag{2}
\]

Values for the average pedaling force applied in all available gear ratios over a variety of cadence values are shown in table 1. Table 1 also shows the pedal speed achieved at each cadence. These values are calculated for a crank length of 172.5 mm.

Table 1. shows average pedaling force and pedal speed calculations.

<table>
<thead>
<tr>
<th>Number of Teeth on Rear Sprocket / Cog</th>
<th>Cd (rpm)</th>
<th>Vp (m/s)</th>
<th>Fav (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>51.1</td>
<td>133.6</td>
<td>77.7</td>
</tr>
<tr>
<td>13</td>
<td>42.5</td>
<td>108.5</td>
<td>63.4</td>
</tr>
<tr>
<td>14</td>
<td>36.0</td>
<td>95.8</td>
<td>52.8</td>
</tr>
<tr>
<td>15</td>
<td>31.0</td>
<td>75.6</td>
<td>44.7</td>
</tr>
<tr>
<td>17</td>
<td>24.0</td>
<td>55.8</td>
<td>33.3</td>
</tr>
<tr>
<td>19</td>
<td>19.3</td>
<td>44.3</td>
<td>31.3</td>
</tr>
<tr>
<td>21</td>
<td>16.9</td>
<td>34.5</td>
<td>31.3</td>
</tr>
<tr>
<td>23</td>
<td>13.7</td>
<td>28.4</td>
<td>33.3</td>
</tr>
<tr>
<td>26</td>
<td>11.2</td>
<td>22.2</td>
<td>33.3</td>
</tr>
</tbody>
</table>

Due to the nature of pedaling, a cyclist will not exert the average pedaling force at all point of pedaling rotation. Instead they will generate larger amounts of force within the effective pedaling range. The force generated in this range, called the effective pedaling force, is defined by Eq. (3) [9].

\[
F_{eff} = \frac{F_{av} \times 360}{2 \times \pi} \tag{3}
\]

Table 2 shows the values of effective pedaling force in each available gear ratio and cadence combination (assuming an effective pedaling range of seventy degrees) [9].

<table>
<thead>
<tr>
<th>Number of Teeth on Rear Sprocket / Cog</th>
<th>Cd (rpm)</th>
<th>Vp (m/s)</th>
<th>Fav (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>51.1</td>
<td>133.6</td>
<td>77.7</td>
</tr>
<tr>
<td>13</td>
<td>42.5</td>
<td>108.5</td>
<td>63.4</td>
</tr>
<tr>
<td>14</td>
<td>36.0</td>
<td>95.8</td>
<td>52.8</td>
</tr>
<tr>
<td>15</td>
<td>31.0</td>
<td>75.6</td>
<td>44.7</td>
</tr>
<tr>
<td>17</td>
<td>24.0</td>
<td>55.8</td>
<td>33.3</td>
</tr>
<tr>
<td>19</td>
<td>19.3</td>
<td>44.3</td>
<td>31.3</td>
</tr>
<tr>
<td>21</td>
<td>16.9</td>
<td>34.5</td>
<td>31.3</td>
</tr>
<tr>
<td>23</td>
<td>13.7</td>
<td>28.4</td>
<td>33.3</td>
</tr>
<tr>
<td>26</td>
<td>11.2</td>
<td>22.2</td>
<td>33.3</td>
</tr>
</tbody>
</table>

Applying a force to the pedals causes the crank to rotate, which imparts a force to the pins in the chain, resulting in a chain tension. This chain tension pulls on the rear sprocket, creating a torque in the rear wheel. The forces applied to the rear sprockets causes the rear wheel to rotate. The rate at which the rear wheel rotates is a function of the gear ratio equation shown in Eq. (4) and the cadence [9].

\[
G_r = \frac{FT}{RT} \tag{4}
\]

Eq. (5) shows how to convert the gear ratio to gear inches. Gear inches is an expression of how big the drive wheel would need to be if it were to achieve the same speeds at a 1:1 gear ratio [9].

\[
G_m = G_r \times D \tag{5}
\]

Eq. (6) shows how to convert gear meters to gear rollout (the distance the bicycle will travel for one rotation of the crank) [9].

\[
G_{mroll} = G_m \times \pi \tag{6}
\]

Calculations for gear ratio, gear meter, and gear roll out are shown in table 3.

Table 3. shows the gear ratio, gear meter, and gear roll out calculations.
Given the gear roll out and the cadence values, the velocity of the bicycle can be calculated with Eq. (7) [9].

\[
V = G_{ro} \times C_d
\]  

(7)

Alternatively, Eq. (8) offers a more direct way to calculate velocity [9].

\[
V = \frac{F}{RT} \times D \times \pi \times C_d
\]  

(8)

Table 4 shows the velocities that can be achieved for each gear ratio at a variety of cadence values.

Table 4. Shows the velocity calculations.

<table>
<thead>
<tr>
<th>Number of Teeth on Rear Sprocket / Cog</th>
<th>Gear Ratio</th>
<th>Wheel Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 50</td>
<td>12 6.23</td>
<td>9.16</td>
</tr>
<tr>
<td>34 50</td>
<td>13 5.75</td>
<td>8.95</td>
</tr>
<tr>
<td>34 50</td>
<td>14 5.34</td>
<td>8.89</td>
</tr>
<tr>
<td>34 50</td>
<td>15 4.98</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>16 4.40</td>
<td>8.56</td>
</tr>
<tr>
<td>34 50</td>
<td>17 3.94</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>18 3.56</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>19 3.34</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>21 2.88</td>
<td>8.46</td>
</tr>
</tbody>
</table>

Table 5 shows the calculations for the force of wind, rolling resistance, and gravity.

Table 5. Shows all three force calculations.

Although cyclists are very concerned with speed, one of the most important things to a cyclist is power output. Power is important because it is needed to overcome the forces acting against the cyclist. The three main forces that a cyclist must combat are the force of the wind (Eq. (9)), the force of rolling resistance (Eq. (10)), and gravity forces (Eq. (11)) [9].

\[
F_w = 0.5 \times A \times C_w \times \rho \times V^2
\]  

(9)

\[
F_{rr} = W \times \frac{9.8 m}{s^2} \times C_{rr}
\]  

(10)

\[
F_g = W \times \frac{9.8 m}{s^2} \times S
\]  

(11)

Table 5 shows the calculations for the force of wind, rolling resistance, and gravity.

Table 6 shows the values that were used for equations (9), (10), and (11).

Table 6. Shows the values used for the Table 5 calculations.

<table>
<thead>
<tr>
<th>Number of Teeth on Rear Sprocket / Cog</th>
<th>Gear Ratio</th>
<th>Wheel Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 50</td>
<td>12 6.23</td>
<td>9.16</td>
</tr>
<tr>
<td>34 50</td>
<td>13 5.75</td>
<td>8.95</td>
</tr>
<tr>
<td>34 50</td>
<td>14 5.34</td>
<td>8.89</td>
</tr>
<tr>
<td>34 50</td>
<td>15 4.98</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>16 4.40</td>
<td>8.56</td>
</tr>
<tr>
<td>34 50</td>
<td>17 3.94</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>18 3.56</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>19 3.34</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>21 2.88</td>
<td>8.46</td>
</tr>
</tbody>
</table>

Table 7. Shows the power calculations.

<table>
<thead>
<tr>
<th>Number of Teeth on Rear Sprocket / Cog</th>
<th>Gear Ratio</th>
<th>Wheel Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 50</td>
<td>12 6.23</td>
<td>9.16</td>
</tr>
<tr>
<td>34 50</td>
<td>13 5.75</td>
<td>8.95</td>
</tr>
<tr>
<td>34 50</td>
<td>14 5.34</td>
<td>8.89</td>
</tr>
<tr>
<td>34 50</td>
<td>15 4.98</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>16 4.40</td>
<td>8.56</td>
</tr>
<tr>
<td>34 50</td>
<td>17 3.94</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>18 3.56</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>19 3.34</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>21 2.88</td>
<td>8.46</td>
</tr>
</tbody>
</table>

Table 8 shows the power calculations for the Table 6 calculations.

Table 8. Shows the values used for the Table 6 calculations.

<table>
<thead>
<tr>
<th>Number of Teeth on Rear Sprocket / Cog</th>
<th>Gear Ratio</th>
<th>Wheel Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 50</td>
<td>12 6.23</td>
<td>9.16</td>
</tr>
<tr>
<td>34 50</td>
<td>13 5.75</td>
<td>8.95</td>
</tr>
<tr>
<td>34 50</td>
<td>14 5.34</td>
<td>8.89</td>
</tr>
<tr>
<td>34 50</td>
<td>15 4.98</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>16 4.40</td>
<td>8.56</td>
</tr>
<tr>
<td>34 50</td>
<td>17 3.94</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>18 3.56</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>19 3.34</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>21 2.88</td>
<td>8.46</td>
</tr>
</tbody>
</table>

Table 9. Shows the power calculations for the Table 8 calculations.

Table 9. Shows the values used for the Table 9 calculations.

<table>
<thead>
<tr>
<th>Number of Teeth on Rear Sprocket / Cog</th>
<th>Gear Ratio</th>
<th>Wheel Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 50</td>
<td>12 6.23</td>
<td>9.16</td>
</tr>
<tr>
<td>34 50</td>
<td>13 5.75</td>
<td>8.95</td>
</tr>
<tr>
<td>34 50</td>
<td>14 5.34</td>
<td>8.89</td>
</tr>
<tr>
<td>34 50</td>
<td>15 4.98</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>16 4.40</td>
<td>8.56</td>
</tr>
<tr>
<td>34 50</td>
<td>17 3.94</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>18 3.56</td>
<td>8.73</td>
</tr>
<tr>
<td>34 50</td>
<td>19 3.34</td>
<td>8.62</td>
</tr>
<tr>
<td>34 50</td>
<td>21 2.88</td>
<td>8.46</td>
</tr>
</tbody>
</table>

DISCUSSION

Despite the fact that bicycles have been around for a long time, they continue to improve. One reason that they continue to improve is because of the demands of racing. Races such as the Tour de France have become extremely popular over the years. Not only have they become popular, but they have also become highly competitive. As a result, there is a great demand for high quality bicycles with superb power transfer. This demand is likely to lead to new, innovative bicycle powertrains. Such changes may come in the form of lighter materials, stronger bottom brackets, or something else entirely.

In addition to racing, bicycle designers are also responding to economic and social needs. As gas prices continue to rise and the concern for the environment grows, people are looking for cheaper, more environmentally friendly modes of transportation. Such demands may lead to bicycle powertrains that do not incorporate chains. Although the chain is fairly efficient, it requires more maintenance than some people desire. Thus, enclosed
powertrains with less maintenance requirements are likely to develop sometime in the future.

CONCLUSIONS AND RECOMMENDATIONS

Over all the bicycle powertrain of the Cannondale R800 is a very good powertrain. The calculations reveal that this specific bicycle offers a wide array of gear ratios, ranging from 1.31 to 4.17. This wide range of gear ratios allows the rider to attain a variety of speeds over the same cadence. The bike, however, is still geared high enough to allow the rider to achieve very high rates of speed. This is good because it allows the bicycle to be used not only for commuting and leisure rides, but also for racing.

One opportunity for improvement in the powertrain would be the addition of either a larger chain ring on the front crank, or a smaller sprocket in the rear cassette. The addition of such sprockets would allow for even greater levels of speed to be attained.

Another improvement would be to lighten up the frame. The issue regarding frame design, however, is that it would not be good to make the bike weaker or less ridged. Doing this could harm the power transfer. Carbon fiber, however, has been proven to be both strong and light. Thus, perhaps a carbon fiber frame would make the bike, lighter, faster, and just about as ridged as the original aluminum design.

Lastly, one might try adding a long crank arm, or a non-round chainwheel. It is tough to say whether or not such a change would be beneficial. This is because not enough tests have been done to determine whether or not longer cranks or non-round chainwheels provide any sort of advantage. Over all the Cannondale R800 has an excellent power train, but like any other bike, there is always room for improvement [9].

REFERENCES

THEORY AND OPERATION OF THE FAIRPORT LIFT BRIDGE

Shaynae Moore
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
The purpose of this paper is to review lift bridge powertrain technology, using the Fairview Lift Bridge located on the Erie Canal, as the main focus. The Fairport Lift Bridge is very unique and is believed to have been featured in the Ripley’s Believe It or Not text. No angles of the bridge are the same and it sits on 32° decline. The bridge is a marvel of its time. The powertrain system of a lift bridge consists of counterweights (usually concrete square blocks), counterweight support cables, sheaves (pulleys), and a motor. These are the most important components. Other components include bearings and fasteners or joints. Based on research, the bearings seem to be an important design component based on the complexity of stresses they undergo. For the simplicity of this review, the bearings will not be heavily discussed since the general dynamics of the system is what is important.

DESCRIPTION OF THE TECHNOLOGY
A powertrain system is a group of mechanical and/or electrical components that generate power to move a larger system. It includes components such as shafts, transmissions, and engines as mentioned previously. Components may or may not change depending on the drivable system.

In this section we will more closely look at the Fairport Bridges’ powertrain components and how they work together. Most lift bridges lifting mechanism is located at the top of the bridge. Steel cables pass over sheaves in bearings and then connect to the lift span of the bridge. The sum of the tension in the ropes is equal to the weight of the span. There are usually only two counterweights; one attached at each end of the bridge. They can be coupled, but this is not optimal for design, as it increases unwanted weight and complicates maintenance and operation. The Fairport Bridge’s power system is located beneath the bridge. Large concrete support slabs house the span’s lift frame.

Figure 1 is a generic schematic of a typical lift bridge system. Modern lift bridges now place the counterweights inside of the bridge’s tower for better control. This helps the prevention of twisting counterweights due to twisting of the cables. Roller guides also are implemented to help with this as well. The bridge’s electric motor has to provide enough power to overcome the static friction forces and weight of the lift span. The lighter the bridge’s dynamic components, the easier it is to move and the less the power consumption. For the Fairport Lift Bridge the, dynamic components are hidden in the support concrete. Essentially the sheaves, counterweights, cables, and motors are located at the ground level instead of atop.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$</td>
<td>angular velocity</td>
<td>rad/sec</td>
</tr>
<tr>
<td>F</td>
<td>force</td>
<td>N</td>
</tr>
<tr>
<td>T</td>
<td>torque</td>
<td>N-m</td>
</tr>
<tr>
<td>I</td>
<td>Rotational inertia</td>
<td>kg-m$^2$</td>
</tr>
<tr>
<td>P</td>
<td>power</td>
<td>Watts</td>
</tr>
<tr>
<td>r</td>
<td>radius</td>
<td>m</td>
</tr>
</tbody>
</table>

BACKGROUND
Lift bridge powertrain technology allows static bridges to become mobile for increased traffic handling. The first documented lift bridge was in Vienna over the Danube River. It spanned about 30 feet and had a maximum lift height of 5 feet. The lift bridge over the England Grand Surrey Canal served as a prototype for lift bridges for over 60 years. The power train systems for these bridges were of the crab and screw type or hand winch, which were powered by men. The concepts are comparable to the spool of a fishing rod. Other bridges use hydraulic motors.
LITERATURE REVIEW

Some great contributors to the development of lift bridge design, other than those previously mentioned were, Captain W. Moorsom who entered a bridge plan, in an international competition in 1850, which would cross the Rhine at Cologne. It spanned had a span of 100 feet. The platform included a crossing for trains, people, and motor vehicles. Oscar Roper designed a lift bridge in 1867 that would allow ships to pass underneath it.

In the latter half of the 19\textsuperscript{th} century, there were many lift bridge designs that began to take notice in the engineering world. Some were very bold for their time spanning up to 300 feet and lifting 90 feet. New counterweight concepts sprang up, such as hollowing out the block of concrete to allow water to pour in for bridge lifting and out for descent. Also, instead of using ropes for bridge suspension, chains were used.

Lift bridge designs eventually incorporated railroads and sidewalks for pedestrians.

Upon completion of the Erie Canal in 1825, the need for more efficient bridges was necessary after attempts at raised fixed bridges and swing bridges failed. In 1872 a patent was granted to Squire Ripple for his design of a lift bridge. The first bridge of his patent type was built on Hotel Street in Syracuse, N.Y. It was suspended from rods that were connected to overhead trusses. The trusses were supported on towers at each end of the bridge. The columns of the bridge’s truss were hollow to allow the rods to move in order to lift the bridge. The bridge’s counterweight materials were cast iron boxes filled with pig iron. The tread wheel for lifting the counterweights was 9 feet in diameter while the sheaves were 3 feet in diameter. Eventually more bridges lift bridges were built along the canal, but were powered by hydraulic motors that that transmitted power to a shaft and pulley system.

The Schaeffler Group is an engineering company in Germany that designed the Spijkenisse vertical lift bridge on the Oude Maas. It has four segments of about 33 feet each. Each span can be lifted independently of one another at a maximum height of approximately 15 feet. Track rollers that contain 168 roller bearings. The Kampen Bridge sheaves are gold plated, and its bearings are doubled row spherical roller bearings.

OPERATION OF THE TECHNOLOGY

A 40 horsepower electric motor is connected to reduction gears. Torque is transmitted through the output motor shaft to the fixed sheave shaft. The power outputs combined with the weight of the counterweights are enough to overcome the weight of the lift span. Grooves in the sheaves help prevent slip of the cables so that the bridge lifts and lowers in a smooth and safe manner. Counterclockwise motor shaft rotation lifts the bridge while clockwise shaft rotation lowers the bridge. More torque power is needed to lift the bridge because of frictional forces and weight, while less is needed to lower the bridge because the drive system is not working against gravity. In the next section we will take a look at torque, and power equations associated with lift bridges.

THEORY OF THE TECHNOLOGY

How do we determine what are the power requirements for the lift bridge? From the static description of the powertrain technology, we use eqn. 1 obtained from the free body diagram.

\[
\Sigma F_y = 0 = W_{\text{span}} - 2W_{\text{counterweight}}
\]

In equilibrium the weight of the bridge will be equal to two times the weight of the counterweights. From the above equation we know the minimum amount of force (pull/push) needed to lift the bridge. This translates into the tension in the ropes and/or tower brace. In the case of the Fairport Lift Bridge, it is pushed from the bottom by the tower brace. They
are a series of beams inside a hollow concrete support. The bracing is connected to sheaves, which is also known as the bridge’s pulley system.

Eqn. 2

\[ \sum T = F \times r = I \frac{d\omega}{dt}, \]

where \( I \) = rotational inertia & \( F \) in this case is the tension in the cables and weight of the counterweights. See Figure 3 for details.

![Figure 3: Schematic of Typical Lift Bridge](image)

Eqn. 3

\[ \frac{T_1}{T_2} = \frac{\omega_1}{\omega_2} = \frac{r_2}{r_1} \]

Eqn. 3 assumes that the rotational inertia for the gears is the same.

Power from the motor transmits through reduction gears to slow down or speed up lift velocity. Slower velocity allows for better control, so a small gear would be connected to the motor, and then a larger gear connected to the sheave shaft. From eqn. 4, you get you power torque relationship. The angular velocity in the power equation is the rotational speed of the motor output gear.

Eqn. 4

\[ P = T \times \omega \]

where \( T \) = torque & \( \omega \) = angular velocity.

DISCUSSION

The previous section is a broad overview of the dynamic theory of powertrain operation for lift bridges. An engineer develops bridge specifications beginning with the span of the body of water it will cross and what type of traffic the bridge will see (i.e. pedestrian, vehicular, boats, etc). From there, the span, width, and the minimum lift height are determined. Then the engineer can begin to design for stresses the bridge will be subjected to, and forces required lifting the bridge and keeping it static in both the raised and lowered conditions.

From eqn. 4 increasing the angular velocity or torque increase the amount of power output. So the more torque necessary to get the bridge moving the greater the power consumption. Manipulating the gear ratios in eqn. 3 changes can increase or decrease the amount of torque input and output from the motor gear and sheave shaft gear respectively. Also, varying the radii of the gears changes angular speed and torque well. Sheaves can reach a diameter up to 12 feet. The important factor to note here is that the dynamic components are what determine the necessary power output from the motor.

CONCLUSIONS AND RECOMMENDATIONS

After studying how typical lift bridges are constructed and how they work, the Fairport Lift Bridge has a lot of benefits to it. The mechanical room that houses its main powertrain components are easily accessible since they are at grade level, there is less weight at the top of the bridge, and it is easier to lift since it is pushed from the bottom instead of suspended and pulled from above. Easier accessibility makes for easier maintenance. Lubricating sheave shaft bearings your typical lift bridge is dangerous since on it has to be done in the air and the bearings never get fully lubricated because there always loaded. Even replacing the bearings can get complicated from so high up.

It was very difficult to find information out there on the Fairport Lift Bridge. I’d recommend visiting the site to get a better idea of its operation instead of solely relying on speculation and video. Also, I’d look into speaking with a NYS Office that is responsible for the bridge. As they would have extensive documentation on it, or know where to seek out the detailed bridges design and construction.
REFERENCES


THE IMPACT OF THE JAPANESE TSUNAMI AND EARTHQUAKE ON THE POWERTRAIN INDUSTRY

Chuck Nwapa
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
This paper focuses on the effects of the 2011 tsunami and earthquake on the Japanese and American Powertrain industry with particular attention on the automakers. It explores the way the earthquake affected business both in Japan and all over the world. The effects of the earthquake on all major automakers in Japan is discussed in full detail. Major topics discussed include the effect of the earthquake and tsunami on the production of hybrid vehicles (Japan is a major manufacturer of hybrid vehicles and batteries), high-end electronic control systems, in-car entertainment devices and CVT transmissions, high thermal resistance plastics for engines, traction batteries for hybrids, stamped steel body parts, automotive electronics. The paper describes the effects of the earthquake and tsunami on the business operations, employment and social welfare of major auto industry participants in Japan and around the world.

NOMENCLATURE
This section outlines any terminology that associated with the topics discussed in this paper.

NPA- National Police Association
Mw- Moment magnitude
OEM-Original equipment manufacturer

JIT-Just In Time Production
EV- Electric Drive Vehicle
IC- Hybrid vehicle

BACKGROUND
The Tohoku earthquake, officially named the Great East Japan Earthquake occurred on Friday, 11 March 2011 with a magnitude of 8.9 ($M_w$) and subsequent 30-foot tsunami occurred in Japan. It had an epicenter approximately 70kilometres (43mi) east of the Oshika Peninsula of Tokohu and the hypocenter at an underwater depth of approximately 32km(20mi). The earthquake triggered a devastating tsunami, which had waves of up to 38 meters while in some cases they travelled up to 10km inland. Dozens of cities and villages along a 1300-mile stretch coastline were shaken by violent tremors that reached as far away as Tokyo, which is hundreds of miles (km) from the epicenter. The earthquake and subsequent tsunami left the nation in a state of disarray and affected the people and industries in Japan in a very negative way. The Japanese NPA confirmed 14,755 deaths, 5279 injured and 10,706 people missing across prefectures as well as over 100,00 buildings damaged or destroyed. Many electrical generators and at least three nuclear reactors suffered explosions due to hydrogen gas that built up within their outer containment after cooling system failure. Residents within a 20km radius of the Fukushima I Nuclear Power plant and a 10km radius of the Fukishima II Nuclear Power plant were evacuated. The earthquake moved the earth on its axis by an approximately 10cm(4in). It is estimated that repair costs would be likely astronomical. It is estimated that those costs would exceed those of the Kobe earthquake of 1995, which was around $120 billion. With Japan being the third-largest producer of automobiles (after China and the US), Japan’s manufacturing network is highly but unusually complex. It is very interdependent so a little hiccup or complications can cause serious problems for the industry. This has led to widespread impact on most auto companies in Japan. Mazda which is located in Hiroshima experienced minimal damage but its plants suspended production because of parts shortages. Nissan, which produces all of its Infiniti brand cars in Japan, had 1300 vehicles destroyed at the Port of Hitachi plus 1000 more at a service center, which impacted exports. A map is shown below showing how the disaster affected the different automobile manufacturers in Japan.

DESCRIPTION OF THE INDUSTRY
The powertrain or power plant refers to the group of components that generate power and deliver it to the road. It includes the engine, transmission, differentials and final drive (drive wheels, differentials and the final drive). Japan is currently the world’s 2nd largest
automobile producing country behind China with 9,625,940 units produced in a year. Japan therefore has a very large influence on the powertrain industry on a global scale. The automotive industry and subsequent powertrain industry as it stands is a very complex industry that has a very vulnerable supply chain where 3000 parts can go into a single car or truck. Each of those parts is made up of hundreds of parts and a delay in the arrival of one of those parts can cause disrupt the assembly of a vehicle. Japan currently has a strong hold in certain aspects of the powertrain market in which many auto manufacturers depend on. High power and high-energy batteries including the equipment for cell manufacturing is an industry that Japan currently has a stronghold on. Japan also supplies computer chips and paint pigments to major car manufacturers on an international scale. Hitachi Automotive Systems, which makes parts such as airflow sensors and drive control systems had some of its factories shutdown. This in turn affected many auto manufacturing companies, which depend on it for those parts. General Motors briefly shut a pickup plant in Shreveport, Louisiana, due to a lack of parts; it caused the closing of a New York factory that supplies engines for those trucks. Japanese suppliers also make many of the electronic components that control music systems and the sensors that monitor fuel levels and airbags. Although many of these Japanese auto parts makers are not located in the areas that were inundated by the tsunami, between damage, electricity outages and water cutoffs, many factories in the region have remained paralyzed ever since. The earthquake and tsunami have generally affected automakers in different ways and to different extents.

Honda
91% of Honda and Acura models are manufactured in North America therefore Honda is feeling a minimum effect of the earthquake as most of its powertrain components for automobiles its automobiles sold in North America are not produced in Japan. However 3 of its Honda plants located in Japan (Tochigi, Saitama and Hamamatsu) where closed immediately after the quake. Tochigi builds engines, transmissions and chassis parts. Saitama builds the CR-V, Accord, Fit and the Acura RL. Honda hybrid models are also experiencing disruptions in supply of auto components because major components of the Honda Prius are manufactured in Japan.

Toyota
Initial effects of the earthquake caused Toyota to shut down several domestic plants. These plants potentially most directly impacted the production of its smaller models such as the Yaris, Scion xB and Scion xD. Toyota’s Lexus line would also be impacted greatly as all Lexus vehicles are produced in Japan. Although most of the vehicles sold by Toyota in North America are produced in America, it obtains up to 15% of the parts used in its North American plants from Japan experiencing shortages of 150 critical parts. It is currently operating at 30% in North America.

A Map of Toyota Production Facilities In Japan

General Motors
GM did not feel an immediate effect of the Japanese earthquake and Tsunami on its operations. However it idles plants initially due to parts shortages but quickly found alternative sources for parts. GM depends on Japan suppliers for about 2% of its entire supply.

Ford
Like GM, Ford did not experience an immediate effect of the earthquake on its production and supply lines but was impacted down the line as its hybrid battery is produced exclusively by Japan-based Sanyo corporation. Ford is also currently experiencing shortages in paint supply for many of its auto models.

LABOR IMPACT
The earthquake and subsequent tsunami in Japan drastically affected the Japanese economy. Some industries would see a boom, e.g. construction industry while others would decline at least in the
short term. However the widespread shutdown of several production plants in Japan created a ripple effect internationally and in the US. Most companies are slowing down production rates in American plants because of the parts shortage in order to control supplies. This in turn would lead to job interruptions especially in Japanese based auto companies with plants in the US such as Honda and Toyota. GM recently shutdown its plant in Shreveport because of the earthquake in Japan. However a reverse scenario can lead to temporary job creation because the earthquake did not affect many US auto manufacturing companies as seriously. Many Japanese based auto manufacturers are also outsourcing their manufacturing jobs abroad so this would create jobs even if its on the short-term basis. This can give the US based companies and other international automobile manufacturers a comparative advantage and push demand for these automobiles, which would in turn ramp up production and jobs.

**CAPITAL INVESTMENT AND VEHICLE SALES IMPACT**

The Japanese auto industry took a huge beating from the recent Tokohu earthquake financially as analysts estimated that many auto companies would lose billions of dollars in revenue as supplies of automobiles produced by this companies are starting to come to a halt as a result of the shortages of key powertrain components that were directly affected by the Japanese earthquake. Goldman Sachs [1] estimates that the earthquake and related shutdowns are costing Japan automakers $200 million a day. IHS automotive [2] predicts that one-thirds of the global automotive production would be cut as a result of the earthquake and tsunami. It is also estimated that over 500,000 vehicles were not produced in the first month after the earthquake and production deficit could reach 1 million by July. Japan also specializes in JIT production philosophy. This philosophy is designed to reduce costs with acquiring and dealing with inventory. Unfortunately this is currently causing major difficulties now that production has been interrupted in Japan. Apart from the reduction in production of cars and parts, export of these goods has also been compromised as roads, ports, infrastructure are also adding to the costs that manufacturers incur. It is estimated that the overall costs of the Tokohu earthquake is put between 100-250 billion USD. However the reconstruction of the country would provide an impetus to the Japanese economy by creating economic activity and a demand for the replacement of cars, which might mean a re-conceptualization of the supply chain. [3].

Currently Toyota, Honda and which are both Japanese car companies are seeing an effect on their sales after the earthquake. According to Time magazine [4] sales of passenger cars have reduced the most by an estimated 39%. Truck sales were down 11%. Toyota and Mitsubishi have experienced the hardest hit since the earthquake. Toyota fell year-on year by around 46% to 110,000 vehicles Mitsubishi lost 48 percent. Nissan and Mazda recorded 38% while Honda recorded a 28% decline. Toyota responded to the decrease in sales with increase in process of it cars to the tone of between (200-900) more depending on the model. On the other hand US auto sales reached a 13 million annual pace due to increasing consumer confidence prior to the earthquake. The shortage of Japanese model cars is set to benefit GM and Ford the most as GM reported a 14% gain in April. GM is said to be managing parts shortages very well and is unlikely to have production disruptions. Ford, which recently received a 2.5 billion dollar first-quarter profit, has also increased sales by 14%. South Korean carmakers Hyundai and Kia also experienced improve sales post earthquake as they appeared to be unscathed by Japanese supply shortages. Chrysler group, which is operated by Fiat, also experienced increased sales. They have sales climb to 18% and reported a profit of 116 million dollars. However further market share shift to American car companies has been offset due to the increasing price of gas.

**PREDICTIONS**

Although the earthquake is still relatively recent some predictions can be made as to the trends that the global auto industry would see post earthquake. Japanese automakers Toyota and Honda are already seeing a shortage in parts and are expected to not be at full operation till at least January next year. This would lead to lower sales and less revenue. These companies would therefore try to offset costs with an increase in costs of automobiles and worldwide cancellations of existing incentive packages. The job market in Japan and worldwide would be altered, as Japanese automakers would outsource jobs outside Japan to accommodate the situation. However American automakers are poised to take advantage of this and would see their sales increase in the short term. They would also take advantage of the necessary cost increases by the Japanese to increase their sales. The global long-term effect will move focus on the energy portfolio and proven technologies like clean diesel technology or natural gas technologies. Green technologies based on IC engines would get a boost while EV plans founded on nuclear energy might experience a slow down.
CONCLUSIONS AND RECOMMENDATIONS

Currently the auto industry is currently intertwined and severely economically globalized. Although it has brought a high division of labor, it also brings a low-cost and high efficiency but this Japanese earthquake has exposed the drawbacks of economic globalization. Japan is currently the largest producer of automotive electronic chips and there is no alternative supply. A problem like this can be solved with the creation of an alternative supply for components. Japan also relies on JIT technology, although this technology is efficient, secondary substitute methods should be created to support it in the event that it fails.

REFERENCES
ABSTRACT

The 2010 Chevrolet Camaro SS has two available 6.2 liter V8’s. The choices are the L99 and the LS3. The L99 comes coupled to the 6-speed automatic Hydra-matic 6L80, while the LS3 is mated to the 6-speed manual Tremec TR6060 [1]. This paper will cover the theory and operation of the Tremec TR6060 manual transmission. The Tremec TR6060 is manufactured by Transmission Technologies Corporation. There are many variations of the TR6060 transmission used in production vehicles today. Versions of the TR6060 are used in such vehicles as the Chevrolet Corvette, Corvette Z06 and Corvette ZR1. Other variations are also used in the Dodge Viper, Dodge Challenger, Pontiac G8 GXP, Cadillac CTS-V, and Ford Mustang Shelby GT500. The differences between the variations used in each car are the torque values that the transmission is rated for as well as the gear ratios. The M10 TR6060 used in the Camaro is rated for 430 ft-lbs of torque.

The TR6060 is derived from its predecessor, the Tremec T56 6 speed manual. The TR6060 was launched for the 2008 model year. The first vehicle it was used in was the Ford Mustang Shelby GT500. It uses synchronized helical cut forward gears and a fully synchronized constant mesh reverse gear system. The main case, extension housing and clutch housing are made from aluminum alloy. It also contains removable wear pads on the shift forks. The key differences between the T56 and the TR6060 are the TR-6060 offers triple synchros on the 1-2 and 3-4 gear shifts (instead of double) and the rest, including reverse get double. The synchronizers have been upgraded from a carbon-particle paper to a sintered-bronze material. The TR6060 has a 26-spline input shaft, up from 10-spline on the T56. The TR6060 also has a stronger transmission case, one-piece countershafts, and the gear faces are wider. All of this results in greater overall strength [2].

Figure 1. The Tremec TR6060 6-Speed Manual Transmission [3].

<table>
<thead>
<tr>
<th>Gear Number</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>3.01</td>
</tr>
<tr>
<td>Second</td>
<td>2.07</td>
</tr>
<tr>
<td>Third</td>
<td>1.43</td>
</tr>
<tr>
<td>Fourth</td>
<td>1.00</td>
</tr>
<tr>
<td>Fifth</td>
<td>0.84</td>
</tr>
<tr>
<td>Sixth</td>
<td>0.57</td>
</tr>
<tr>
<td>Reverse</td>
<td>3.28</td>
</tr>
</tbody>
</table>

Table 1. Gear Ratios for the 2010 Camaro SS with the Tremec TR6060 6 Speed Manual Transmission [3].

The TR6060 used in the Camaro has a transmission cooler for proper temperature control. The M10 TR6060 weighs 146.2 lbs with oil in it [3-6].

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR</td>
<td>Gear Ratio</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Number of teeth on gear</td>
<td>#</td>
</tr>
<tr>
<td>d</td>
<td>Diameter of gear</td>
<td>inches</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Greek Symbols</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega )</td>
<td>Rotational Speed</td>
<td>(rad/s)</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Torque</td>
<td>(ft-lbs)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subscripts</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>in</td>
<td>Input to the System</td>
<td>-</td>
</tr>
<tr>
<td>out</td>
<td>Output from the System</td>
<td>-</td>
</tr>
</tbody>
</table>
BACKGROUND

Manual transmission technology is important because it is used in so many vehicles. This technology is used in passenger cars, trucks, and motorcycles. The technology varies slightly between different types of vehicles, but all follow the same principles.

The manual transmission design requires the use of all the core mechanical engineering courses. Statics, mechanics and dynamics are used in the structural components, including the gears, shafts, bearings, hardware and casings. Fluid mechanics are used to understand the lubrication of the gears with oil. Heat transfer and thermodynamics is used to understand the heat produced through friction and how it is dissipated throughout the transmission.

The technology used in the manual transmission consists of gears, friction clutches, bearings, splined shafts, shift rods and shift forks.

Almost all motorcycles use a manual transmission. This is also true for most heavy duty trucks, such as tractor trailers. The transmissions range from two speed manuals in some small motorcycles, all the way up to 18 speed tractor trailers. In the United States 91 percent of the passenger vehicles sold have automatic transmissions. The number of manual transmissions sold throughout the world is higher. Although the amount of manual transmission vehicles sold has slowly decreased over the years, there is still a market for them [7].

The manual transmission is a mature technology. The modern manual transmission was invented in the late 1800’s. The Panhard-Levassor transmission of 1894 is what the modern manual transmission is based off of [8].

DESCRIPTION OF THE TECHNOLOGY

The technology used in the Tremec TR6060 is much like that used in most modern manual transmissions. Figure 2 is a schematic of an actual Tremec manual transmission. Figures 3-5 are shown for visual explanation of the internal components of the manual transmission.

The transmission starts at the flywheel which is bolted directly to the engine’s crankshaft. The single plate clutch disk is then held in place by the pressure plate which is between the diaphragm spring and the friction plate. The clutch disk is splined at the center. The clutch disk rides on the splined input shaft of the transmission [9].

Next in line is the transmission itself. The input shaft enters the transmission; this is shown in green in Figure 3. Next is the layshaft (shown in red in figure 3) which is coupled to an assortment of gears. These gears mesh with the gears riding on bearings on the output shaft (shown in blue in Figure 3). The output shaft is shown in yellow in Figure 3. Splined to the output shaft is the collars, shown in purple. Also contained within the transmission are the gear selector forks. The TR6060 contains removable wear pads on the shift forks. There is an idler gear mounted between the gear on the layshaft and the reverse gear mounted on the output shaft. This is shown in Figure 4. The blue gear is mounted on bearings on the output shaft and the red gear is coupled to the layshaft via keyways. The purple gear is the idler gear, mounted between the other two gears. Synchronizers can also be found in the TR6060 transmission. An example of a synchronizer is shown in Figure 5. The synchronizer consists of both the blue cone portion of the blue gear as well as the yellow cone shaped portion of the collar [10].
The modern manual transmission was introduced by Louis-Rene Panhard and Emile Levassor of France in 1894. Their initial multi-gear design was not taken well as the motor on the demonstration vehicle broke down and they were forced to describe their technology to the press using a chalk board. With no demonstration, most people thought it was a gimmick and one news reporter stated that their invention was “more hocus-pocus from charlatans trying to cash in on the public’s fascination with the new motor car.” One year later, in 1895 the Panhard-Levassor drive-train was revolutionary. Not only did they develop the new transmission, but they introduced a whole new drivetrain layout. Their design consisted of a vertically mounted engine in the front of the vehicle that drove the rear wheels. The rear wheels were driven through a clutch and 3-speed sliding gear transmission. Unlike modern cars, Panhard-Levassor’s vehicle had a chain driven axle rather than a driveshaft, differential and axles. Panhard-Levassor’s drivetrain served as the basis for most vehicles built in the 90 years following their discovery. A diagram of their drive train is shown in Figure 6.

The rear differential, axle and driveshaft were invented three years later, in 1898 by Louis Renault. He connected a vertical engine and transmission to a live rear axle using a metal shaft. Renault adapted the live rear axle from an idea developed by C. E. Duryea in 1893. The live axle, or differential axle used multiple gears to allow the outer driving wheel to rotate faster than the inner driving wheel. This eliminated tire scuffing in turns and therefore overcame the problem of rapid tire wear.

The Panhard-Levassor sliding gear manual transmission was adopted by most carmakers by 1904. The basic design of the Panhard-Levassor transmission is still used today. There have been many improvements to their design over the years. The most significant improvement was the introduction of synchronizing systems. The synchronizing system allows the drive and driven gears to mesh with each other smoothly without clashing or grinding. It allows both sets of gears to reach the same speed before they are engaged. The first synchronesh transmission was introduced by Cadillac in 1928. Porsche improved upon the Cadillac design and patented it. Porsche’s design is still widely used today [8].
The crankshaft of the LS3 engine rotates clockwise. The flywheel is bolted directly to the crankshaft and therefore also rotates clockwise. The clutch rides between the pressure plate and the flywheel. The clutch center is splined and rides on the input shaft of the transmission. When the clutch is engaged (the driver’s foot is not on the pedal) the diaphragm springs in the clutch assembly push the pressure plate, pressing the clutch against the flywheel. When this happens the clutch moves at the same speed as the flywheel and spins in a clockwise direction to transfer the power from the flywheel to the transmission input shaft. Next the clockwise rotation is transmitted from the input shaft to the layshaft which has a set of gears that are keyed to it. Next, the counter-clockwise rotating gears on the layshaft are meshed with a set of gears running on bearings on the output shaft. There are collars splined to the output shaft. These collars have dog teeth so that they can mesh with the gears on bearings on the output shaft. The Tremec TR6060 has synchronizers to improve gear changes. These synchronizers consist of a cone shaped portion of the gears on the output shaft as well as a cone shaped portion within the collar. The purpose of this is to allow the gears and collars to come up to the same speed as the cones begin to mesh together. This helps with the engagement of the dog teeth of the collars into the gears on the output shaft. Synchronizers help prevent grinding. The power is then transmitted through the gears riding on the bearings and into the collars. These are now moving clockwise. The collar transmits this clockwise rotation to the output shaft which it is splined to. The output shaft supplies rotational motion directly to the driveshaft which is now rotating clockwise. From the driveshaft, power is sent through the rear differential to turn the rotation 90 degrees to rotate the axles. The axles transmit power to the hubs and wheels and finally to the road.

Shifting occurs by the driver first depressing the clutch pedal. When the clutch pedal is depressed a hydraulic piston pushes the release fork, pushing the throw-out bearing against the middle of the diaphragm spring. The middle of the diaphragm spring will get pushed in and a series of pins at the outer edge of the spring, attached to the clutch cover, causes the spring to pull the pressure plate away from the clutch allowing the clutch to disengage from the spinning flywheel. Now that the clutch is no longer coupled to the flywheel, the driver can use the gear select lever to change gears. When the driver moves the gear select lever the gear selector fork will move the collars into contact with a gear on the output shaft. Moving the different collars into contact with the different gears selects different gear sets with different ratios.

When the driver puts the transmission into reverse the collar’s dog teeth mesh with the reverse gear on the output shaft. The layshaft is rotating counterclockwise. The rotation is transmitted to an idler gear which is then spinning clockwise. The idler gear transfers its rotation to the gear that is riding on a bearing on the output shaft. This gear is now rotating counter-clockwise. The dog teeth of the collar mesh with this gear, turning the output shaft in reverse (counter-clockwise, opposite of the normal rotation of the output shaft). This in turn rotates the driveshaft counter-clockwise, and the vehicle moves in reverse.

**THEORY OF THE TECHNOLOGY**

The basic premise for the quantitative theory of the manual transmission is gear ratios. The following equations show the relationship between input gear number of teeth versus output gear number of teeth, input torque versus output torque, as well as input speed versus output speed and how they all relate to gear ratios.

\[
GR = \frac{N_{\text{out}}}{N_{\text{in}}} 
\]

(1)

\[
GR = \frac{\tau_{\text{out}}}{\tau_{\text{in}}} 
\]

(2)

\[
GR = -\frac{\omega_{\text{in}}}{\omega_{\text{out}}} 
\]

(3)

The following figure shows how gear ratios are calculated within a manual transmission. It shows that the gear ratio from the input shaft to layshaft has to be multiplied by the gear ratio from the layshaft to the output shaft to get the total gear ratio. This same process is used for all the gears within the transmission. The only difference with reverse is that it uses an idler gear between the layshaft and output shaft.

![First Gear Ratio Example](image)

**Figure 8.** First Gear Ratio Example [14].

\[
GR = \frac{N_D N_B}{N_C N_A} = \frac{40 \times 35}{18 \times 23} = 3.38 
\]

(4)
The helical cut gears used in the TR6060 have an efficiency of 98.99%. The remaining 1-2% is lost to heat. The heat is not insignificant and for this reason the TR6060 uses a transmission cooler.

The tangential force on each gear at the point at which they mesh is equal and opposite. The force is found below [14].

\[ F_1 = \frac{\tau_1}{d_1} = -\frac{\tau_2}{d_2} = -F_2 \quad (5) \]

**DISCUSSION**

The technology used in the Tremec TR6060 is tried and true. The manual transmission has been around since the beginning of the automobile. Even with the years and years of development, the technology is always advancing. Advancements continue to be found in materials to allow the transmissions to be lighter and stronger. One of the largest changes that continues to evolve is material used for the clutch. Different combinations of carbon and metallics are used to allow the right amount of friction, heat dissipation, and weight. In many cases the formula for the clutch material is proprietary information for each supplier. Each has their own top recipe that they do not want to get out to their competitors. Other changes include the number of clutch discs used as well as the layout of the clutch. Advancements continue to be made in synchronizer mechanisms, seals, bearings, lubricants and additives [15].

Although automatics make up 91 percent of the market share for vehicles sold in the United States in 2009, there will always be a desire by car enthusiasts for a manual transmission. There is also an increase in types of available transmissions including single and dual clutch automated transmissions. These automated transmissions allow the driver to drive in automatic mode or shift the vehicle themselves but without the use of a manual clutch. The clutch is fully automated by the computer. Even though these transmissions can be considered faster and more efficient, many true driving enthusiasts still prefer the traditional manual transmission [7].

Most of the funds and research for technological progress will be devoted to the new automatics as well as the single and dual clutch automated transmissions. These are the transmissions of the future for fuel economy and ease of use. While most of the funds will be devoted to the automatics, a fair amount will still be used to perfect the manuals for the true driving enthusiast. Also, any advancement in clutch materials used for the automated transmissions can also be utilized in the manuals [7].

**CONCLUSIONS AND RECOMMENDATIONS**

I believe that the technology used in the Tremec TR6060 is great. The transmission shifts smoothly and uses all of the latest manual transmission technology such as triple synchronizers on the first to second gear shift as well as the third to fourth gear shift. It uses double synchronizers on the rest of the gears in the transmission including reverse. It is a robust transmission, as can be seen by its use on so many high torque, high performance vehicles. It is also a proven design and technology that has seen many advancements over the years.

The technology is always improving. A lot of the improvements are in materials. I think this is the main place that can be improved in manual transmissions. Due to their nature of being manually controlled by the driver, there is not much improvement that can be had in the sense of functionality. If anything were to change in the function, such as an automated clutch, it would no longer be a true manual transmission. In the material area there is always improvement. This was seen in the move from carbon-particle paper to a sintered-bronze material in the synchronizers. Different materials could also be used for the clutch friction plate as well as for the transmission casing to increase strength and reduce weight.

**References**


Copyright © 2011 Rochester Institute of Technology


THEORY AND OPERATION OF THE TOYOTA “ECT-i” ELECTRONICALLY CONTROLLED AUTOMATIC TRANSMISSION

ZEESHAN PHANSOPKAR
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
At present consumers want increasingly advanced levels of performance from cars. Hence an automatic transmission must deliver basic requirements as well as performance requirements like optimum shift, efficient transmission of engine torque, smooth shifts, excellent response and reliability. Because of these rigorous requirements, a hydraulically controlled automatic transmission has reached its limits in a number of aspects [1]. Also, with a hydraulically controlled automatic transmission it is difficult to achieve integrated control with the components of other vehicle system.

Fuel economy improvement in automobiles is one of the main prerequisite for effective utilization of the limited source of fuel. Countless efforts have been made to design more fuel efficient automatic transmissions while providing higher levels of vehicle performance and passenger comfort [2]. As the electronic control concepts advance, its application has potential solution to better fuel economy requirements in the automotive sector. The necessity for communication between the other automobile electronic systems and transmission, offers motivation for need of electronic control system for transmission. The standard functions of electronic transmission systems have demonstrated their value and elevated the level of vehicle performance [3]. Because of this, in spite of the added cost, almost all automatic transmission will be electronically controlled in the next few years [3].

Toyota “ECT-i” electronically controlled automatic transmission is called the A341E. This transmission employs a unique engine and transmission integrated intelligent control system named “ECT-i”, and a high performance “Super flow” Torque convertor. This control system is capable of total control of engine torque and clutch hydraulic pressure during shifting, which has resulted in very smooth shift without changes over the life of the transmission [4].

This paper describes the Toyota “ECT-i” automatic transmission with intelligent electronic control system, focusing mainly on basic concepts, construction and effectiveness for the A341E transmission.

BACKGROUND
Every vehicle needs a Transmission to convert the torque and rotation. Without the transmission cars would be limited to single gear ratio. Therefore, a Transmission system is essential to transform the power from the engine into vehicle traction as efficiently as possible, over an extensive range of road speeds. The four chief functions of a vehicle Transmission are: Moving off from rest, changing ratio, shifting power flow and controlling the gearbox [5]. Vehicle transmissions are technically and technologically highly mature mass produced products. They are categorized as greatly advanced technologies. Transmission system development is aimed principally at increasing fuel efficiency and reducing emissions.

In the early seventies, the first electronic control systems appeared on the market. These were simple transistor control units for actuating in/out valves, and were capable only of determining shift points [3]. At the beginning of the eighties first microcomputer controls were presented [3]. The first transmission with fully electronic microprocessor control of all major functions appeared on the market in 1983 [3]. This was ZF’s 4 HP-22, a 4-speed automatic transmission with hydrodynamic torque converter and lockup clutch for vehicles with rear wheel drive. The electronic control function was performed by a microcomputer, enabling substantial functional improvements to be achieved [3, 6]. This system included number of technical features that are currently considered as a state of the art for electronic transmission control systems.

The usage of electronically controlled Automatic transmission systems has become more and more popular now due to advancements in technology and demand for higher performance response from the automatic transmission and shift comfort of the vehicle, with reliability over life of transmission.

Copyright © 2011 Rochester Institute of Technology
Figure 1. Distribution of electronic transmission control for passenger cars adapted from [3].

Figure 1 shows a study of cars manufactured in the USA, Europe and Japan in 1989, it indicates that in the USA, the percentage of electronically-controlled automatic transmissions is still low and that for Europe is not very high yet either, as shown by the Fig. 1 [3]. The percentage of electronically-controlled system is large in Japan. One of the principal causes for this is unquestionably the added cost. However, the data represents a totally misleading picture of the future. Almost 100% of all recently designed automatic transmissions for passenger cars are electronically controlled [3].

DESCRIPTION OF THE TECHNOLOGY

In today’s automobile, the current automatic transmission is undoubtedly, the most complex mechanical module. Automatic transmissions contain hydraulic systems, mechanical systems, electrical systems and computer controls, all functioning together in seamless synchronization to drive the system.

The term “Fully Automatic Transmission” is applied to geared transmission in which two part functions ‘engaging drive’ and ‘changing gear’ are carried out automatically in accordance with fixed or adaptive programs.

The main components of an automatic transmission are:

1. Torque converter.
3. An Electronic control system.

Figure 2 shows a detailed view of a typical automatic transmission.

As shown in Figure 4, the A341E consists of the power transmission system with a torque converter and gear train, and the control system with sensors, ECU, and electronically controlled hydraulic control unit.

Figure 3. Configuration of the A341E Transmission. Adapted from [4]

Torque Converter:

Torque converters are fluid coupling that utilize hydrodynamic principles to amplify the torque input to the transmission. It consists of an impeller, turbine and a fluid pump. The pump is the driving member and the turbine is the driven member.

The only connection between the pump and the turbine is the working fluid. The “Super Flow” torque converter was used for A341E for V-8,4.0 liter engine. Figure 4 shows a sectional view of it.
Planetary Gear Set:

Planetary gear set forms a vital part of an automatic transmission. A planetary gear set comprises of a sun gear in the center, a planet carrier with the planets mounted to it, and a ring gear with internal teeth. To transmit torque one of the elements must be fixed. Planetary gear set provides the several forward gear ratios in addition to reverse; however they are never physically moved as in manual transmission.

Figure 5 shows the sectional view of the A341E transmission. A forward Four speed gear train, consisting of three pairs of simple planetary gears with high reliability and a high degree of freedom which allows the compact structure, used as a gear train. The overdrive mechanism is installed between the torque converter and the third gear unit, which facilitates the size reduction [4].

Control System:

Sensors:

This system has 12 sensors including the pattern selection switch. The accurate synchronization of the initiation and completion of the upshift with the initiation and completion of the inertia phase is necessary for engine torque control [4].

Electronic control unit (ECU):

The ECU is aimed at upgrading reliability, cost, and size reductions by integrating the ECT control unit and the engine control unit [4].

Actuators:

Electronic control of the clutch hydraulic pressures in shift operations is indispensable to the attainment of smooth shifts. Therefore, a new linear solenoid valve was developed for the A341E and installed for the transmission clutch hydraulic control and lock-up clutch hydraulic control. It consists of an electromagnetic portion to generate appropriate loads in line with values of current, and a pressure regulator portion to generate hydraulic pressures proportional to the loads [4].

The main functions of the control system are engine torque control and clutch hydraulic pressure control.

Working Fluid:

Special organic oil known as Automatic transmission fluids ATF have been developed for use in automatic transmissions. The fluid used in A341E is named Type T II ATF. It has special features, low temperature viscosity characteristics and shudder resistance, with only small changes over system life [4].

LITERATURE REVIEW

From [7], Since 1930s the automatic transmissions for passenger cars have been developed. Beginning from the 2-speed, the 3-speed, the 4-speed automatic transmissions to 5-speed and 6-speed automatic transmissions used currently. In 1990s, major car and transmission manufacturers introduce 5-speed automatic transmissions successfully. Until late 1970s, the automatic transmissions had adopted hydro-mechanical control systems for automatic gear shifting. From 1980s, the electro-hydraulic control systems of automatic transmissions have been significantly developed to improve fuel economy and realize smooth gear shifting. Also, the solenoid valves which have high pressure and large flow capacity with small size and low cost, to use as electro-hydraulic actuators were technologically developed. These days, consumers want the better shift feeling and new functions like manual shift. To meet these needs, use of more electro-hydraulic actuators and sensors was not a costly solution [7].
In early 1980s, electronic control units (ECUs) were introduced and rapidly spread over the automotive industries. It replaced the hydro-mechanical components with the electro-hydraulic ones only for a few years. This trend made the actuators and the sensors cheaper and cheaper, and changed the system architecture from the passive to the active with the more advanced actuators and sensors [7].

From mid-80s, more electronic control functions had been applied to the automatic transmissions. An electronically controlled solenoid valve substituted for the mechanical link to the accelerator pedal. The ECU read the information such as the throttle opening and the vehicle speed from the various sensors, and determined the shift timing and controlled the pressure of friction elements to get a better shift feeling [7].

Philip G. Gott used the terminology, full electronic control, in his book at the first time. In the viewpoint of hydraulic systems in automatic transmissions, the meaning of full electronic control is that each friction element can be controlled by the ECU independently. In 1990s, along with the advanced technologies of the electronic control and sensors and actuators, it is possible to realize this concept with low cost and reliability [7] [8].

**OPERATION OF THE TECHNOLOGY**

![Figure 7. Electronic control of the automatic gearbox adapted from [9].](image)

A simple block diagram of the electronic car management with a controller area network (CAN), which is responsible for data exchange between the different electronic devices in the car is shown in Fig. 7 [9]. During a gear shift operation, two clutches are operating simultaneously, one clutch engaging and the other one disengaging. The clutch pressure is determined by the electronic control unit (ECU) and applied by the hydraulic device of the gear box. At the same time, the engine torque is reduced by the digital motor electronics (DME) by retarding the ignition timing or adjusting the throttle opening [9]. The engagement and disengagement of the shift elements lead to a system with time varying structure. This is a simple model to illustrate the basics of power shifting.

The Electronic control transmission uses modern electronic control technologies to control the transmission. The transmission is virtually the same as hydraulically controlled transmission, but it also consists of electronic parts, sensors, an electronic unit and actuators [10]. The electronic sensors monitor the speed of the vehicle, gear position selection and the throttle opening, sending this information to the ECU. The ECU then controls the operation of the clutches and brakes based on this data and controls timing of shift points and torque converter lock-up. The ECU controls two solenoid valves based on vehicle speed, throttle opening angle and mode select switch position [10].

**DISCUSSION**

The main advantages of electronically controlled automatic transmission are improved drivability, enhanced shift refinement, interaction with other electronic systems, and protection against incorrect operation by driver. The only drawback is fuel consumption which is slightly higher than manual transmission [3].

Among the various technical trials present for developing this new transmission, control and system dynamics are critical for the realization of the fuel consumption and emission benefits while delivering greater performance. Advances made in recent years for the use of electronic control method for automatic transmissions of passenger cars are remarkable, which is successful in improvements in fuel economy, drivability, and shift quality [4].

Development work is concentrated primarily on refining existing functions. Certainly, in recent years one of the main development urgencies has been to upgrade shift programs [3]. By introducing adaptive functions and self -teaching algorithms, significant progress has been achieved, rendering manual program selection obsolete from a technical viewpoint [3]. The objective is to achieve even improved adaptation of the shift programs to current operating conditions and to the individual characteristics of the driver himself. This requires identification of the driver, the vehicle condition and the traffic situation to match its shift strategy to constantly changing conditions. Due to which the cars now feel different as previously we had to adjust according to the conditions as the transmission had fixed logic, however, now the electronic control of the shift program adapts to the changing conditions constantly giving a superior driving experience.

The model A341E “ECT-i” is currently installed in the “Lexus LS400,” a luxury and high performance car of Toyota and has gained a favorable market reputation [4].
CONCLUSIONS AND RECOMMENDATIONS

This paper described the A341E which has a basic construction and to this construction has been added an electronic control system which delivers optimum control over the hydraulic pressures to match the engine and vehicle operating conditions.

The model A341E “ECT-i” is currently installed in the Lexus LS400. Because of the use of the engine and transmission integrated intelligent control system, the A341E transmission is capable of detection and comparison of input and output rotational speeds with high precision. It is also capable of accurate determination of inertia phase conditions, and the total control of engine torque reduction, return timing and clutch hydraulic pressure [4]. The clutch hydraulic pressure control in particular permits the optimum shift under any circumstances, and it has been verified that smooth shifts are ensured without any significant changes over the life of the transmission [4].

Electronic control of Automatic transmission has become an established concept, in spite of the greater cost associated with it. The existing needs for comfort, shift, drivability, and the necessity for interaction with other automobile electronic systems, are the key factors for the popularity of this technology. Absence of electronic control system would restrict the new developments, in my opinion. The regular functions have demonstrated their worth and showed significant contribution towards enhanced drivability and improved refinement. Control of Engine torque unlocks fresh possibilities for optimizing shift refinement, the amount of power that can be transmitted and the life of friction elements [3]. With use of dynamic shift programs, drivability will be further improved. For optimizing fuel consumption wide gear spreads make sense. In particular these demands would be satisfied by new systems which are going to be the 5-speed Automatic Transmissions and Continuous Variable Transmission [3].

REFERENCES

ABSTRACT
Limited slip differentials (LSD) have greatly improved the capabilities of the modern automobile. LSD’s can increase occupant safety, decrease gas consumption and raise driver enjoyment. Through their use, traction has been improved without sacrificing handling. There are two main types of limited slip differentials, Torque-sensitive, and Speed-sensitive. Torque-sensitive differentials relay on a difference in the torque requirements of each wheel to properly distribute available engine torque. Speed sensitive differential use a variety of technique to recognize, and then equalize wheel rotation speed. There are many ways power distribution occurs; a few of the more common methods will be discussed.

NOMENCLATURE

Symbol   Description   Units
LSD       Limited slip Differential   -
ABS       Anti-lock breaking system   -

BACKGROUND
The ultimate goal of any LSD is to improve the automobile’s safety and performance. By comparing the power distribution techniques of old, live axels and single wheel drive, the benefits of limited slip differentials are evident.

In a solid axel both wheels would spin simultaneously at the same rate. This is great for traction because both wheels are providing the same amount of force to the ground. If one tire begins to slip hopefully the opposite tire still has traction can propel the car forward without sacrificing speed and control. However this set-up is bad for cornering performance. While cornering the outside wheel must travel farther because it has a larger radius to cover. With a live axel, turning would require one or both tires to slip to some degree during the turn. This greatly decreases handling performance and could cause the car to lose control and potentially spin completely around. Loss of control is a serious safety concern for drivers and passengers. An image of a live axel is provided below.

DESCRIPTION OF THE TECHNOLOGY
There are many different types of differentials and each has its own unique set of operational features. Both speed sensitive and torque sensitive differential try to distribute power to both wheels. Some descriptions of the more popular types are provided below.

Speed-sensitive differentials tend to be quieter and simpler then their torque sensitive counter parts.
Either through the use of electronics and high viscous fluids the differential notices a difference in rotational velocity. If one wheel is spinning a lot faster then the other the differential will try to even out the difference. This is also advantageous during slippery conditions when one wheel may be slipping but the other is not.

The two main types of torque sensitive LSDs are gear-based, and clutch-based, and they all accomplish the same task. Torque sensitive differentials employ the various methods to more adequately distribute torque to the wheels. Using a series of mechanical parts, the differential notices which wheel has better traction and then puts more torque through that wheel. This is advantageous for if one wheel is slipping (zero traction) a certain percentage will be sent to the other wheel to help maintain control of the car. Nothing is with out disadvantages, torque sensitive differentials can be noisy and can fail in a “locked position”, causing both wheel to spin together effectively making a live axel condition.

LITERATURE REVIEW

There are many differential corporations working on differentials. A big focus is on improving geared differentials. On of the first effective differential was developed by ZF (engineering firm hired by Porsche) in 1935. The need came from a grand Prix invented in 1932 by Ferdinand Porsche for the Auto Union Company; the car experienced excessive wheel spin from one rear wheel [3]. In the 1950’s and 1960’s many car manufacturers started applying brand names to their respective LSD’s. The Torsion differential was invented by Vernon Gleasman in 1958, who then sold it to the Gleason Corporation. In 1982 the Gleason Corporation started marketing the torsion differential to various car manufacturers.

Audi is putting a lot of work into better performing differentials. Their new sport differential uses aspects of multiple styles. When the car senses what one wheel is slipping, and even during normal cornering the differential redistributes the engine power. The onboard system calculates the ideal distribution for the specific situation and controls a hydraulic pump that either pumps fluid to the left or right axel. The fluid is used to compress a set of clutch disks (simulate to clutch differential) thus forcing more torque to that wheel [6]. This is a very active control system using aspects of clutch, and electric differentials.

OPERATION OF THE TECHNOLOGY

The classical or “open” differential used a system of planetary gears to control the wheels. The planetary gears were attached to the differential case. The case was rotated using another gear attached to the drive shaft. As the casing rotated the planetary gears would push on the sun gear and ring gear. This would allow one tire to spin slower then the other, but the fastest it would be allowed to go is the rotational velocity of the differential case. This system worked for many years but, this style would allow for one wheel to be held stationary; allowing the car to get stuck. Below are descriptions of a few differential types that allow traction to both wheels.

Electric speed sensitive differentials use much of the technology already present in the car. At the heart of the system is an open differential. By using the anti-lock breaking sensor (already in place) to read the wheel speed the computer can determine if one wheel is spinning much faster then the other. The control system then applies the brake to the faster wheel, providing resistance. This resistance spends more power through the differential to the opposing wheel [3]. This set-up is extremely cheap and easy to do because all the components are already in place. There is some lag time as the computer calculates what to do, but it is highly tunable. The driver can change speed difference limits, braking force and delay reaction time.

Dilatant fluids can also be used in differentials. In this configuration there is a series of perforated disks inside a sealed chamber filled with this fluid. The disks are attached to each half of the axel in alternating sequences. The wheels are spinning at the same rate the fluid is also moving because of the shear imparted on it by the plates. The torque is split up evenly between each wheel. However when one wheel begins to spin at a different rate then the other a shear gradient is formed in the fluid. This gradient effects both disk faces. The slower disk is dragging the fluid with is dragging the faster plate. The faster plate is trying to pull the fluid along, which tries to pull the slower disk. The greater the difference in relative speeds the greater the shear force in the fluid, creating a greater difference in torque distribution [1]. One great advantage of this system is that it is a “soft” system. When there is a minor difference there is a minor force and it increases with difference in rotational speed. This is excellent for wear because
there are no hard of sudden changes in forces, and there are also less parts in contact so wear is minimal [3]. However if a leak should form the system will fail to operate.

**Figure 2.** This figure shows the internals of a cone style clutch differential. [1]

Gear differentials relay on worm gears to distribute torque. They are very similar to open differentials in set-up. Worm gears serve as the planetary gears except that there are generally two interconnected sets [1]. One set is attached to one side of the axel with the other set is attached to the other. These systems are not very common, mostly found in some all wheel drive applications. Unfortunately they behave the same as an open differential during total slip conditions; all the torque is outputted through the free spinning wheel.

Clutch type LSDs respond to the torque output of the driveshaft. The axels are connected through the use of a series of clutches in contact. Half are attached to one axel, and alternating the other half is attached to the opposite axel. When there is a large torque difference the internal pressure rings are forced sideways by the pinion cross shaft trying to climb ramps (teeth cut into the spider gear). As they are forced out the normal force between the clutch disks increases, increasing the friction and equalizing the torque between each wheel. In low torque differences the force between the plates is less, thus allowing slippage, and one wheel to spin. Generally these differentials have quick response time and the highest strength, however they can be noisy, and expensive so they are mostly used in off-road vehicles [3].

**Figure 3.** This figure shows the internals of a clutch differential. [1]

Another style of differentials that use a clutch are clutch-cones. This configuration contains tapered tubular clutches, and gears. As one wheel spins faster it causes a clutch to get drawn into the housing more. This creates a higher friction between the surfaces, forcing more torque to the opposite wheel [2]. These systems can be complex and engage unexpectedly if the clutch cone does not get released properly.

**Figure 4.** This figure shows the internals of a cone style clutch differential. [2]

**DISCUSSION**

There has been a lot of progress in power distribution and control since the invention of the horseless carriage. This technology has been around for many years in various forms. It has mostly been passive systems in that it reacts to wheel slippage. While purely reactive systems have served humanity reliably for decades, its time for an upgrade. Most modern automobiles will never drive over lose soil, and modern tires maneuver wet/slippery roadways better the tires of old. However active systems are just becoming more reliable and usable. Active systems, such as the Audi sport differential, actively monitor road condition and driver input to distribute power.
This is the future of differentials. As horsepower increases, weight decreases and people desire safe, reliable, and fun to drive vehicles this technology must develop. New, young driver’s tend to desire increased road performance over other factors; where as their parents care about the vehicles safety. Active systems will satisfy this consumer need. Active systems can not only handle slippery conditions but also increase performance on dry pavement, as the Audi Sport Differential does. These types of systems will continue to increase in popularity, and as they do the number of roadway crashes and deaths will decrease. Efficient and well controlled systems could even increase gas mileage by more efficiently using the available power. The potential complexity of such active systems can be seen below in the diagram of an Audi Sport Differential.

Figure 5. Audi Sport Differential [7]

As electric vehicles become more popular the possibilities are endless. While current differentials, and those still in development will be effective, suppose each wheel had its own drive motor. Not only will wheel speed be monitored but the torque being provided to each wheel can also be measured. These capabilities could lend to traction control ten fold. If the car is turning the computer can automatically adjust to wheel speeds. If one tire begins to slip that drive motor can slow down to the exact speed where it is no longer slipping. More power can be allocated to a wheel with high traction so that control can be maintained. Unfortunately the systems required to control all these variables would be extremely complex, and a failure could be disastrous.

There is room for great progress within the realm of traction control. Better, more efficient passive systems will increase safety and reliability while keeping cars affordable. Active systems, while more complex and expensive have endless possibilities, especially with electric automobiles.

CONCLUSIONS AND RECOMMENDATIONS
Limited slip differentials have lead to great advancements to automobile performance. For better or for worse cars can now handle worse conditions. When the weather was bad drivers used to stay home, with advancements these drivers can now have the confidence that they will be safe driving in questionable conditions. While this confidence may lead to more accidents, the control provided by the differential has decreased the severity and saved many lives. It is especially helpful when roadway conditions suddenly change either due to material or weather. This alone has saved many lives.

The specific style that works best really depends on the type of car and the driving style used. If the car will spend a lot of time off road, or in slippery conditions an open differential is not ideal. A torque sensitive, specifically a clutch based system would probably be best. For a sports car that will never be out in slippery conditions an open differential would be sufficient. Race cars would probably find viscous fluid differential ideal because there wouldn’t be sudden changes, and at high speeds that can be dangerous. But, for the average user electric differentials are more then efficient, and very cost effective.

There is still a lot of opportunity for advancement. Active systems still have a long way to go before they can be economically installed in affordable cars. Active systems in performance cars (road and off road) will allow the car to maneuver at greater speeds safely. In passenger cars these systems will decrease tire and bearing wear, ultimately prolonging the life of the automobile and saving the owner money. Active systems will be beneficial especially in northern environments, when there is potential for ice and snow at anytime for half the year. The potential of these systems is tremendous and must be developed further in the coming years.

Currently there is a big crunch to increase gas mileage. Differentials are a major component of that drive train. Increased development and efficiency can lead manufactures to increase gas mileage without decreasing power, ultimately making the car more desirable. While gas cars are here to stay for many years, electric cars can not be over looked. Safety and performance can not be sacrificed in the name of preserving natural resources. As electric cars become more and more common more focus will have to be put towards these drive train systems.

As with any technology safety is the biggest driving force for development. Any thing that can be done to increase occupant safety should be actively perused. Unfortunately a safe car does not account for irresponsible driving.

REFERENCES
2011.
OPERATION OF THE GENERAL MOTORS TURBO-
HYDRAMATIC 400 AUTOMATIC TRANSMISSION

Brad Sawyer
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT
The Turbo-Hydramatic 400 automatic transmission was released by General Motors in 1964 to replace the current automatic transmissions being used at the time. The automatic transmission allows for gear shifts to be made without any input from the driver and also eliminates the need for a clutch. The Turbo 400, as it is commonly called, is known for its great strength and durability. This paper will explore the inner workings of the Turbo 400 and how the transmission allows for a variety of gear ratios to be generated all whilst shifting smoothly between gears. The secret of the Turbo 400 transmission is the use of the Simpson planetary gear set. The Simpson planetary gear set consists of two compound planetary gear sets that share a common sun gear. Different gear ratios are produced by holding certain members of each planetary unit stationary, while allowing others to rotate. An array of multi-disk clutches and band clutches are used to bring power to members of each planetary as well as hold others stationary.

The Turbo 400 transmission utilizes a complex hydraulic system to control all functions of the transmission. The valve body is located on the underside of the transmission and is the hydraulic “brains” of the transmission. While some of the basics of the hydraulic system will be discussed, the complex workings of the valve body will not be explored.

DESCRIPTION OF THE TECHNOLOGY
The Turbo 400 transmission is designed to be used in rear wheel drive vehicles. In the rear wheel drive configuration the transmission sits behind the engine. The transmission mates to the rear of the engine via a bolt pattern on the bell housing of the transmission. The bell housing is the front part of the transmission case which is flared out to accommodate the torque converter. It obviously gets its name from its bell-like shape which can be seen in Figure 1. The more slender part of the transmission behind the bell housing is where the gears and clutches reside. Underneath this section is the transmission fluid pan which functions as a reservoir for the transmission fluid. Inside the pan, the valve body is bolted to the bottom of the transmission. The rear-most part of the transmission is the tail shaft housing. This is where the drive shaft is inserted to mate with the tail shaft, or output shaft, of the transmission.

The input shaft is somewhat shrouded under the bell housing of the transmission. Inspection of Figure 1 reveals that there are actually two shafts that protrude from the front of the transmission. Both shafts insert into and engage the torque converter. The outer shaft, which is also the shorter of the two, is a stationary shaft. This shaft is splined to the stator inside the torque converter and holds the stator stationary. The input shaft rides inside the stationary shaft and is splined to the turbine inside the torque converter.

Figure 1. A view from the front of a Turbo 400 transmission. The bell housing can be seen with the
through holes around its perimeter to bolt it to the back of the engine. Under the bell housing the input shaft can be seen protruding from the front pump [1].

The front pump is located inside the bell housing at the front of the transmission. Both the fixed stator shaft and the input shaft protrude from the front pump. The front pump can be removed from the transmission case by removing bolts around its perimeter and pulling it straight toward the front of the transmission. If one were to pull the front pump out of a transmission, they would notice that the front pump can be split into two sections. Splitting the front pump apart reveals its pumping mechanism which is a gear pump. Figure 2 shows the gear pump in detail. Two teeth can be seen on the inside of the smaller gear. The front snout of the torque converter inserts into the front pump. The annulus that the snout inserts into can be seen surrounding the stator shaft in Figure 1. The snout of the torque converter has two notches which engage the teeth on the gear pump. Since the torque converter housing (and snout) are bolted to the flywheel they are constantly rotating when the engine is running. Because of this, the gear pump is always running when the engine is running, even if the car is in neutral or park.

Figure 2. Looking at the backside of the front half of the Turbo 400 front pump. Both the inner and outer gears rotate and mesh. The two teeth on the inner diameter of the small gear engage the two matching notches on the torque converter snout [2].

The interior of the Turbo 400 transmission consists of 3 multi-disk clutch packs, 4 main shafts, 2 sprag clutches, 2 band clutches, and 2 compound planetary units. The clutches are wet clutch designs and therefore need transmission fluid to operate properly. All components in the transmission operate in a bath of transmission fluid. The 4 main shafts include the input shaft, intermediate shaft, tail shaft, and the common sun gear which is concentric with the intermediate shaft but turns independent of it. Figure 3 demonstrates the layout of the 4 shafts in the Turbo 400.

Figure 3. The shaft layout of the Turbo 400. The input shaft as well as the front drum are highlighted in red. The intermediate shaft plus the forward drum and rear ring gear are highlighted in blue. The sun gears and sun gear shaft are highlighted in green, and the tail (output) shaft along with the rear carrier and front ring gear are in orange [3].

Torque is first transmitted to the input shaft by the torque converter. The input shaft is connected to the front drum. The front drum is connected to two sets of clutches. The first set is the forward clutch, and the second set is the direct clutch. When the forward clutch is engaged, torque is brought to the forward drum and when the direct clutch is engaged, torque is brought to the direct drum. The forward drum is connected to the intermediate shaft and the direct drum is connected to the sun gear shaft. The intermediate shaft runs all the way down the center of the transmission to the rear planetary where it connects to the ring gear of (and serves as the input to) the rear planetary. Consistent with the design of the Simpson planetary unit, the sun gears of the front are rear planetary units are connected by a shaft. Both the rear planet carrier and the front planetary ring gear are connected to the tail shaft and serve as the output of the system.

The intermediate clutch is the rear-most clutch assembly of the 3 disk clutch packs in the transmission. This clutch locks the sun gear shaft to the transmission case when engaged, thus making the sun gears immobile. The intermediate clutch drum is connected to the sun gear shaft through a sprag clutch which engages when the sun gear shaft tries to counter-rotate against the input shaft. This clutch is known at the intermediate sprag. There is also a roller-type sprag clutch which is connected to the reaction carrier drum. The reaction carrier drum houses the front planet carrier. The low roller clutch (named because it is only used in low (1st) gear) keeps the front carrier from rotating in the same direction as the input shaft.

The two band clutches is the Turbo 400 wrap around their respective drum, and when applied, they keep that drum from rotating. The forward-most band keeps the direct drum from rotating. The rear band
wraps around the reaction carrier drum and keeps in it from rotating when applied.

OPERATION OF THE TECHNOLOGY

The heart of the operation of the Turbo 400 transmission is the Simpson gear set which consists of the front and rear planetary gear sets connected by a common sun gear. By manipulating the 3 clutch packs and 2 band clutches in the transmission, the Simpson gear set can produce 3 forward gear ratios and one reverse ratio. The clutches are actuated hydraulically using pressurized transmission fluid from the front pump. Pressurized fluid is routed to the correct clutches by the value body which serves as the “brain” of the transmission.

When the transmission is in park or neutral, and the engine is running, torque is brought to the transmission via the input shaft. This brings rotational power to the front drum, but in neutral or park no clutches are engaged. The power flow stops at the front drum and the engine is effectively decoupled from the rest of the drivetrain.

First gear power flow is shown in Figure 4. Torque from the engine is brought to the input shaft via the torque converter. The input shaft then brings torque to the front drum. The forward clutch is engaged which transfers the torque from the front drum to the forward drum. Since the forward drum is splined to the intermediate shaft, the intermediate shaft brings the torque to the rear planetary. The intermediate shaft connects to the rear planetary ring gear. At this point, the rear planetary ring gear is rotating with the input shaft. The rear planetary carrier is fixed to the tail shaft. Since the vehicle is either at rest, or traveling at low speed when the Turbo 400 is in first gear, the rear carrier acts as a stationary member. With the rear ring rotating with the input shaft, and the rear carrier fixed, the rear sun gear counter-rotates. The gear ratio coming out of the rear planetary is 2.08:1. Since the sun gears are connected by a shaft, the input to the front planetary is the sun gear which is counter-rotating the input shaft. The front carrier is held from rotating by the low roller (sprag) clutch. Since the front carrier is held stationary, the front ring gear will rotate opposite the front sun gear. The front sun gear is counter-rotating the input shaft, therefore the front ring gear will rotate in the same direction as the input shaft. The front ring gear is connected to the tail shaft and is the output of the system. The gear ratio achieved by the front planetary is 1.19:1 and therefore the final ratio for first gear is 2.48:1.

Figure 4. First gear power flow in the Turbo 400. Items highlighted in green are turning with the input shaft. Items in blue are rotating in the opposite direction of the input shaft, and items in red are stationary. The forward clutch is engaged [3]. Second gear involves only the rear planetary of the Simpson gear train. Torque is brought to the transmission by the input shaft which also rotates the front drum. The forward clutch is engaged which brings torque to the intermediate shaft. The intermediate shaft then brings torque to the rear ring gear. The rear ring gear is rotating with the input shaft. At the same time, the intermediate clutch is engaged. The intermediate clutch locks the intermediate drum to the outer transmission case. The intermediate drum is connected to the sun gear shaft through the intermediate sprag clutch. The sprag clutch does not allow the sun gears to counter-rotate the input shaft with respect to the intermediate drum. Because of this, the sun gears are stationary in second gear. With the rear ring gear rotating with the input shaft, and a stationary rear sun gear, the rear carrier will rotate with the input shaft. The rear carrier is connected to the tail shaft and therefore becomes the output. The final ratio for second gear is 1.48:1. The front planetary lies idle in second gear. Figure 5 shows the power flow in second gear.
Figure 5. Second gear power flow in the Turbo 400. Items highlighted in green are turning with the input shaft. Items in blue are rotating in the opposite direction of the input shaft, and items in red are stationary. The forward clutch is engaged along with the intermediate clutch which holds the sun gears stationary [3].

Third gear power flow once again begins with torque being brought in by the input shaft to the front drum. The forward clutch is engaged bringing power to the forward drum and the intermediate shaft. This brings power to the rear ring gear. The direct clutch is also applied which brings power to the sun gear shaft. This means that both the rear sun gear and rear ring gear are rotating at input shaft speed and also in the same direction as the input shaft. When two members of a planetary are rotated at the same speed and direction, all members 'lock' together and rotate as one unit. This means that the rear carrier rotates at the same speed as the input shaft. Third gear in the Turbo 400 is a 1:1, or direct drive, ratio. Figure 6 shows the power flows for third gear.

The mechanics of the second to third gear shift should be noted. In second gear, the intermediate clutch holds the sun gear shaft stationary. In third gear the direct clutch drives the sun gear shaft at input shaft speed. The intermediate sprag clutch allows for this shift to happen smoothly in the Turbo 400. Without the sprag clutch, the release of the intermediate clutch and the application of the direct clutch would have to be timed perfectly to achieve a smooth shift. The sprag clutch allows for the sun gear shaft to free-wheel with respect to the intermediate drum when the shaft is turned in the same direction as the input shaft. Because of the sprag clutch, the intermediate clutch can actually remain engaged while the direct clutch is engaged and the sun gear shaft will turn freely of the intermediate drum. The most common example of a sprag clutch at work is in a bicycle. When load is applied to the pedals in the forward direction the clutch locks the pedals to the rear wheel, but if the pedals are stopped or are turned opposite the rear wheel rotation, the pedals can free-wheel.

The reverse gear of the Turbo 400 uses only the front planetary while the rear planetary idles. In reverse, the torque enters the transmission through the input shaft and then to the front drum. The direct clutch is engaged which brings torque to the sun gear shaft. The front sun gear rotates in the same direction as the input shaft. The rear band clutch is applied which holds the front carrier stationary. The front ring gear now turns opposite the input shaft. The tail shaft is connected to the front ring gear so therefore the tail shaft turns opposite the input shaft, giving a reverse gear. Figure 7 demonstrates the power flow in reverse gear.

Figure 6. Third gear power flow in the Turbo 400. All components of the Simpson gear set are green meaning they turn in the same direction as the input.

Figure 7. Reverse power flow of the Turbo 400. Only the front planetary is utilized. Items highlighted green are turning at input speed, items highlighted blue are turning opposite the input shaft and items that are red are stationary.

THEORY OF THE TECHNOLOGY
The operation of the Turbo 400 automatic transmission relies on the theory of planetary gear sets. The planetary gear set consists of three members, the
sun gear, planet gears, and ring gear. Planetary gear sets have many advantages. High gear reduction can be achieved in a compact unit, and they are capable of handling high power densities. Probably the most desirable attribute of the planetary gear set is that multiple ratios can be achieved from one gear set.

One factor that greatly influences the performance of a planetary gear set is its ‘K’ factor. The ‘K’ factor is the ratio between the number of teeth on the ring gear to the number of teeth on the sun gear. As the ‘K’ factor gets closer to one, the ring gear and sun gear become closer in size, and therefore the planets become smaller. The ‘K’ factor of a planetary directly correlates to the gear ratio that it will provide. Equation 1 shows how the ‘K’ factor is determined. ‘K’ factor is the number of teeth on the ring gear over number of teeth on the sun gear [4].

\[ K = \frac{N_R}{N_S} \] (1)

The direction in which each member will rotate in a given scenario is best described by a nomogram. Figure 8 is the speed nomogram for a planetary gear unit. For each scenario a straight line is drawn and crosses the central horizontal axis at the vertical line that represents the member that is being held stationary. This straight line has a positive slope.

Figure 8 provides a quick method of determining the rotation on each member in different situations. If the sun gear is held stationary, the carrier and ring gear will rotate in the same direction. If the carrier is held stationary, the sun and ring gears will rotate opposite of each other. If the ring gear is held stationary, the sun and carrier will rotate in the same direction.

DISCUSSION

The Turbo-Hydramatic 400 transmission served a long campaign in production vehicles, and is still used in the aftermarket today. Most aftermarket applications are for high performance or racing. The technology used in the Turbo 400 is no longer cutting edge, but the concepts and architecture of the transmission laid the groundwork for its successors. The Turbo 400 was ruled obsolete in production vehicles when rising fuel prices and increased fuel efficiency concerns prompted the design of overdrive transmissions. The two main overdrive transmissions that replaced the Turbo 400, the 200-4R and 700-R4, borrowed many of the design features of the Turbo 400 transmission.

Furthering the idea that the Turbo 400 was an excellent design is the fact that it is still used today in the aftermarket. The Turbo 400 is revered for its strength and durability, along with its simplicity and ease of repair and modification. The stock Turbo 400 transmission was rated to handle approximately 450 horsepower and 500 pound-feet of torque. Some modified Turbo 400 transmissions are capable of handling 2,000 horsepower in drag racing applications.

Modern 4, 5, and even 6 speed automatic transmissions still retain the general design concepts used in the Turbo 400 transmission. The 4L-80E transmission which was used in GM trucks and SUVs up until 2007 is considered a direct decedent of the Turbo 400. The major innovation which has been introduced since the Turbo 400 is electronic control of the transmission. Application of the clutches is still performed by hydraulics powered by a front pump, but some of the routing of the fluid is performed by solenoids instead of the intricate circuit of check values and spool values as was in the Turbo 400.

One problem with the Turbo 400, and all automatic transmissions is that they consume a certain amount of power produced by the engine. This could
be considered a parasitic loss. The internal friction of the gears and bearings along with the power needed to run the front pump, internal inertias of the drums and shafts, and the windage losses from the transmission fluid all combine to create a sizable power loss. If the automotive industry wants to create more efficient cars, the automatic transmission as it stands now may have to go the way of leaded gasoline.

CONCLUSIONS AND RECOMMENDATIONS
The Turbo-Hydramatic 400 served its purpose well, but the future of automatic transmissions as they appear now may be limited. The Turbo 400 was an incredibly robust design, but because of its revered strength and toughness, it is also heavy and inefficient by modern standards. The movement toward electric cars or electric hybrids may make the automatic transmission obsolete. This would be a positive movement from an efficiency standpoint.

Direct drive motors could eliminate the need for a transmission at all, saving both weight and cutting parasitic losses in the powertrain. Electric drive motors can produce peak torque at low RPM, and therefore do not require dynamic gear reduction.

For the time being, the industry is ‘stuck’ with the automatic transmission. Advanced electronic control of the transmissions functions have helped from an efficiency standpoint, but the fact that clutches are still hydraulically actuated limits the efficiency of the transmission as fluid still needs to be pressurized by the front pump. If the industry could find a way to actuate clutches without the use of hydraulic power then it would help from an efficiency standpoint.

No matter what the future of production vehicles brings, one can rest assured that the Turbo-Hydramatic 400 will still be seen behind racing engines for some time into the future. It is not too often that 50 year old technology is still the choice of high performance minded people.

REFERENCES
www.kilgoretrans.com
[2] Super Chevy Magazine Online
“TH400 Transmission Rebuilt, Trans-Former”
TOYOTA PRIUS; TOYOTA HYBRID SYSTEM

Jon Shannon
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

This paper aims to describe in detail the theory and operation of the Toyota Hybrid System (THS) powertrain, first introduced in the popular Toyota Prius passenger car in 1997. The THS was developed by Toyota to create an environmentally responsible automobile meant to help in the global effort to diversify fossil fuel resources and reduce harmful CO₂ emissions [1]. By combining the use of an efficient gasoline engine, an electric motor and an electric generator, Toyota was able to achieve unprecedented fuel economy without sacrificing vehicle size, thus creating a marketable and desirable vehicle. Cars utilizing the THS do not require external charging, thus, the Prius, and other hybrid vehicles, can be nearly twice as efficient as comparable conventional vehicles, yet still utilize the existing gasoline infrastructure found worldwide [1].

The following sections will explain in detail what a hybrid system is, how Toyota has utilized a hybrid powertrain so successfully, and what the most recent advancements in the THS have done for the company. Toyota’s cutting edge Hybrid technology has begun to change the face of the automobile industry while simultaneously changing the public’s perspective of affordable, practical and fuel efficient vehicles. The Toyota Prius is a testament to the ability of Engineers to shape a global market and advance a seemingly stagnant idea (the automobile) to a better, more efficient and desirable product.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>frontal area</td>
<td>(m²)</td>
</tr>
<tr>
<td>C_D</td>
<td>drag coefficient</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
<td>(ppm)</td>
</tr>
<tr>
<td>CVT</td>
<td>continuously variable transmission</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>generator</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>electric motor</td>
<td></td>
</tr>
<tr>
<td>R_fd</td>
<td>final drive reduction ratio</td>
<td></td>
</tr>
<tr>
<td>THS</td>
<td>Toyota hybrid system</td>
<td></td>
</tr>
<tr>
<td>T₀</td>
<td>output torque</td>
<td>(Nm)</td>
</tr>
<tr>
<td>V</td>
<td>vehicle velocity</td>
<td>(m/s)</td>
</tr>
<tr>
<td>c_f</td>
<td>fuel consumption rate</td>
<td>(g/s)</td>
</tr>
<tr>
<td>c_f</td>
<td>fuel economy</td>
<td>(km/l)</td>
</tr>
<tr>
<td>g</td>
<td>acceleration of gravity</td>
<td>(m/s²)</td>
</tr>
<tr>
<td>hp</td>
<td>horsepower</td>
<td>(hp)</td>
</tr>
<tr>
<td>η_fd</td>
<td>final drive efficiency</td>
<td></td>
</tr>
<tr>
<td>µ</td>
<td>rolling resistance coefficient</td>
<td></td>
</tr>
<tr>
<td>rød</td>
<td>tyre radius</td>
<td>(m)</td>
</tr>
<tr>
<td>ω₀</td>
<td>output ring gear speed</td>
<td>(rad/s)</td>
</tr>
<tr>
<td>τ</td>
<td>Torque</td>
<td>(N·m)</td>
</tr>
</tbody>
</table>

BACKGROUND

Hybrid vehicle technology is an emerging trend in the automobile industry which has developed in response to rising fuel costs worldwide, combined with public and government concerns regarding fuel economy and vehicle emissions. Toyota is at the forefront of the current hybrid car transition, and the company is experiencing global success with the THS. Currently, the Toyota Prius is among the most efficient cars on the market, however, smaller and lighter gasoline powered vehicles are beginning to reach similar gas mileage markers. The difference is that a Prius contains the same interior space as a midsized car. Hybrid powertrain systems allow for car manufacturers to increase fuel mileage without compromising overall vehicle size, which also helps with safety ratings. Another difference between a hybrid vehicle and a gasoline vehicle is CO₂ emissions. Vehicle emissions count for nearly 25% of the total green house gas emissions in the United States [2]. This becomes an even bigger issue when considering congested American cities with many vehicles and high population densities. Since, while in traffic, hybrid vehicles shut off the gasoline engine and run solely on the electric motor, vehicle emissions in a congested city can be greatly reduced using hybrid vehicles. While a mass transition to hybrid vehicles will not save the remaining fossil fuel supply, or eliminate all vehicle emissions, it is a step in the right direction. Toyota’s success of the THS demonstrates the general public’s interest in driving more fuel efficient vehicles. The resulting corporate push toward developing and implementing hybrid systems will undoubtedly advance the technology much further in the future, and perhaps facilitate a transition to a plug-in electric vehicle infrastructure.

At the end of 2010, Toyota had sold over two million hybrid Prius vehicles worldwide [3]. In 2010, the Prius
only accounted for less than 1% of total global passenger car sales, however, in 2011 global hybrid car sales are expected to reach one million for the year. If this figure is reached, hybrid car sales will account for roughly 2% of the passenger cars sold worldwide [4]. Perhaps the best way to demonstrate the importance of Hybrid vehicle technology is a direct comparison of the emissions of a hybrid vehicle versus a similarly sized gasoline vehicle. Figure 1 shows the comparison of a 2010 Ford Fusion and a 2010 Toyota Prius emissions and gasoline consumption driving 14000 miles per year.

**Figure 1.** Hybrid versus conventional car emissions comparison [5].

The Prius emitted 4659 fewer pounds of harmful emissions and burned 244 fewer gallons of gasoline over the course of one year. It is undeniable, the positive affects an increased market share of hybrid vehicles could make on global gasoline consumption and vehicle emissions.

**DESCRIPTION OF THE TECHNOLOGY**

The Toyota Hybrid System is the existing technology found in the Toyota Prius which links an electric motor to an internal combustion engine, producing a parallel-series hybrid powertrain. Consider figure 1 below which illustrates the basic component layout of the THS.

**Figure 2.** Basic component layout of the Toyota Hybrid System.

For energy storage, the THS contains both an 11.9 gallon gasoline fuel tank as well as a 21 kW output nickel-metal-hydride battery pack. The gasoline fuel tank directly supplies fuel to the 76 horsepower, 1.5 liter, four cylinder internal combustion engine. The battery pack stores electricity generated by the engine’s generator and regenerative braking system, and also supplies electricity to a 67 horsepower, 295 ft-lb of torque, permanent magnet motor. The most critical component of the THS is the power split device which acts as a continuously variable transmission (CVT) interconnecting the engine, generator, and electric motor. This power split device is what makes Toyota’s hybrids different from other car manufacturers, allowing the car to be powered by (1) the gasoline engine alone (2) the electric motor alone or (3) a combination of both the electric motor and engine together. Using the power split device enables the engine to run at an optimal rate all the time, thus burning the least amount of gasoline required. When this optimal rate produces excess power than what is required, the generator charges the battery pack, when the car requires more energy than the motor can produce at its optimal rate, the electric motor supplements the engine. Toyota’s power split device consists of a planetary gear set as shown in figure 2.

**Figure 3.** THS’s power split device shown as planetary gear set.

The sun gear of this planetary gear set is coupled to the engine’s generator, the ring gear connects to the electric motor, and the planetary carrier connects to the engine. This gearing allows the hybrid system to act in a parallel-series fashion, giving the Toyota Prius its exceptional fuel economy.

**LITERATURE REVIEW**

The history of hybrid motor technology is longer than you may think. As far back as the late 1800s, inventors were constructing electrically powered vehicles, while some where including a gasoline motor and a generator to supply electricity to the motor. It wasn’t until 1968 that something close to the modern hybrid powertrain was developed. Between the years 1968 and 1971 Dr. Baruch Berman, Dr. George H. Gelb and...
Dr. Neal A. Richardson of TRW developed and patented an electromechanical transmission which used a smaller than usual internal combustion engine supplemented by an electric motor [6]. Some hybrid technology ideas first drafted by these men are still in use today. In the 1970s, the Arab oil embargo caused the price of gasoline in the US to soar, which resulted in a major push toward continuing research in Hybrid powertrains, as well as electric vehicles. In 1976 U.S. Congress enacted Public Law 94-413, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act. In 1997, Toyota released the Prius into the Japanese auto market, marking the first hybrid car available to the general public by a major auto company [6]. Since 1997, hybrid cars have been introduced in every major automobile market in the world, and hybrid technology has been adopted by most major automakers.

Currently, the limiting factor in hybrid car technology is the battery pack. The current THS uses a nickel metal hydride battery pack that is 53.3kg (117.5lbs) and is what limits the car from using more electrical power, and thus further increasing gas mileage and reducing emissions [7]. Current research and development for hybrid technology is focused on battery technology. Currently lithium-ion battery technology seems to be the answer. Li-ion batteries have a higher energy density than nickel metal hydride batteries, thus, for the weight of the battery pack, more energy can be stored and drawn in one battery cycle. For an example on the importance of battery technology, in 1997, General Motor’s EV1 electric car had a lead-acid battery pack weighing 1200lbs and measuring nearly eight feet in length. Currently, the Chevrolet Volt electric vehicle utilizes a lithium-ion battery pack, storing the same amount of energy as the EV1, however, the pack only weighs about 400lbs and measures about five feet [7]. Li-ion batteries are tricky because presently there is much debate as to which material should be used for the cathode. There are many different cathode material choices, each changes the energy density and cost of the battery pack. Undeniably, the biggest factor limiting further efficiency gains from hybrid vehicles is the battery pack, the most expensive and important element of the system.

Additional research is being done on fine tuning the optimal engine operation point in order to maximize fuel efficiency in planetary gear hybrid powertrain vehicles. KukhyunAhn, Sungtae Cho, Suk Won Cha, and Jang Moo Lee discuss the variables such as planetary gear ratios, input torques from the gasoline engine and generator, steady state analysis, engine efficiency and transmission losses and how all these variables combine to change the optimal operation point for any given series/parallel hybrid powertrain [10].

**OPERATION OF THE TECHNOLOGY**

As previously discussed, the Toyota Hybrid System operates by using a planetary gear set to operate on either the internal combustion engine, electrical drive motor (M-fig. 4), or both simultaneously.

![Figure 4. Relevant THS components](image)

There are six operational situations in which the Prius has been designed to run under. I will discuss each situation from the vantage point of power as it is introduced and expelled from the powertrain system.

**Situation 1: Start and low speeds.** Starting from rest and when operating at speeds under 24km/h (15mph) when there is sufficient battery charge, power is supplied by the battery pack and is used directly by the electric motor M to drive the wheels.

**Situation 2: Cruising speed.** Operating at constant speeds, the gasoline engine supplies power to the planetary gear set. From here, power is split between the generator G and the drive shaft turning the wheels. The generator supplies electric power to drive the wheels via motor M and supplement the mechanical power of the engine.

**Situation 3: Sudden acceleration.** When the car is accelerated suddenly (i.e. when overtaking another vehicle or climbing a hill) power is supplied to the system from both the battery pack and the gasoline engine together. The engine spins the generator, supplying power to motor M, and drives the wheels directly. Motor M also drives the wheels, receiving power from the battery pack and generator G.

**Situation 4: Braking.** When decelerating and braking, the gasoline engine is shut off and the electric motor M acts as a generator, converting mechanical energy from the wheels to electrical energy, which is stored in the battery pack.

**Situation 5: Battery recharge.** When the battery pack requires charging, the gasoline engine supplies power to generator G, which converts mechanical energy to electrical energy to recharge the battery pack. This situation can be initiated during any of the aforementioned operating situations.

**Situation 6: Rest.** While the vehicle is at rest, the gasoline engine does not run and the battery pack...
retains its charge. There is no power supplied to the powertrain [1,9].

THEORY OF THE TECHNOLOGY

A large portion of the theory behind the operation of the Toyota Hybrid System depends on the planetary gear which is used to split power among the components of the powertrain. Figure 5 depicts how each part of the THS is connected to the planetary gear set.

![Figure 5. The THS planetary gear set [1].](image)

As depicted in fig. 5, the sun gear is coupled to generator G, the ring gear is coupled to motor M and the planetary carrier is coupled to the gasoline engine. When considering the most efficient possible operation of the THS, Ahn and his colleagues explain the theory behind the powertrain well in their published paper entitled Engine Operation for the Planetary Gear Hybrid Powertrain [10]. In this paper, it is determined that at cruising conditions (situation 2 from the previous section) the output ring gear speed and output torque from the hybrid powertrain can be used to find the system optimal operation point.

\[
\omega_o = \frac{V}{r_{tyre}} R_{id} 
\]  

(1)

\[
T_o = \left(\frac{1}{2} C_D \rho A v^2 + \mu Mg\right) \frac{r_{tyre}}{R_{id} \eta_{id}} 
\]  

(2)

\[
e_f = \frac{V \rho_{gas} g}{c_f} 
\]  

(3)

By using the output ring gear speed (1), output torque (2) and fuel economy (3) while considering the parameters listed in table 2 of Ahn and company’s paper, the optimal operation speed for that vehicle was determined to be between 40km/h and 60km/h [10]. As one can recognize, many parameters must be considered in the theory of the operation of the Toyota Hybrid System, as the system is a complex balance of many different components. Toyota engineers have the ability to tune the THS in different ways in order to for the vehicle to operate at peak efficiency in different driving conditions.

DISCUSSION

The future for hybrid vehicle technology looks promising. The global effort to reduce harmful vehicle emissions and increase the efficiency of vehicles will only continue to grow as fossil fuel resources continue to dwindle. Presently, hybrid vehicles are a good way to proceed, since the vehicles can utilize the existing fossil fuel infrastructure worldwide. Nearly every major car company has released or has announced the release of a hybrid vehicle in their product line for the US market. Sales of the Toyota Prius have led the way since the car’s release in 1997, and the continual research and success of the car’s powertrain is evident in the sequential release of the 1st, 2nd and 3rd generation Prius. I see future hybrid vehicles having a more powerful battery system, and more advanced energy recovery system while also supporting plug-in capabilities. While all-electric vehicles and different alternative fuel options must be considered in the distant future, I believe for the next 20 years hybrid cars will become the norm for passenger vehicles worldwide.

REFERENCES


TRANSMISSION / GEAR RATIO OPTIMIZATION

Mason Verbridge
Mechanical Engineering Student
Rochester Institute of Technology

ABSTRACT

The paper serves to research feasible options for creating a custom manual transmission for a lightweight, affordable sportscar. Design efforts focus on basic material selection and the optimization of the transmission gear ratios. The material selections are made based on cost, weight, and structural characteristics. The gear ratios are iteratively optimized based on three resulting criteria: a) Vehicle 0-60 mph time b) Vehicle 0-100 mph time c) Fuel economy during a standardized EPA test

The optimization will be achieved using a custom MatLab script. The assumptions and their effects are covered, and suggestions for future improvements to refine the accuracy of the model are covered. Although the specific gear ratios cannot be released, the qualitative results of the optimization will be discussed.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description (value if constant)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>vehicle frontal area (1.9 m²)</td>
<td>m²</td>
</tr>
<tr>
<td>ANET</td>
<td>instantaneous net acceleration (m/s²)</td>
<td>m/s²</td>
</tr>
<tr>
<td>Cd</td>
<td>vehicle coefficient of drag (0.28)</td>
<td>-</td>
</tr>
<tr>
<td>Crr</td>
<td>rolling resistance coefficient of tires (0.0125)</td>
<td>-</td>
</tr>
<tr>
<td>Doff</td>
<td>drive train efficiency (0.9)</td>
<td>-</td>
</tr>
<tr>
<td>Fa</td>
<td>acceleration force produced by engine</td>
<td>N</td>
</tr>
<tr>
<td>Fnet</td>
<td>net acceleration force (accounts for resistances)</td>
<td>N</td>
</tr>
<tr>
<td>Fd</td>
<td>drag force</td>
<td>N</td>
</tr>
<tr>
<td>FD</td>
<td>final drive</td>
<td>-</td>
</tr>
<tr>
<td>Fer</td>
<td>force of rolling resistance</td>
<td>N</td>
</tr>
<tr>
<td>g</td>
<td>gravity (9.81 m/s²)</td>
<td>m/s²</td>
</tr>
<tr>
<td>GRi</td>
<td>gear ratio of specified gear i</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviations

EPA Environmental Protection Agency
PSAT Powertrain Systems Analysis Toolkit
RPM Engine Speed, Revolutions Per Minute
U.S. DOE United States Department of Energy

BACKGROUND

Transmission optimization and material selection are important steps in the drivetrain design process. Materials should be selected to withstand any and all of the loading conditions seen in the field while remaining as lightweight and affordable to manufacture as possible. Gear type, tooth profile, and overall gear geometry have significant effects on the stress in the gear. These aspects, along with many
Others, must be considered before choosing a material with the appropriate properties.

For gear ratio optimization, the goal is to meet the target characteristics of the vehicle using as few gears as possible. Primary goals for this vehicle include a broad operating range (0-120 mph), good fuel economy in the commonly used speed range (0-65 mph), and good acceleration from 0-60 mph and 0-100 mph. By nature, the fuel economy typically prefers a “longer” or higher ratio gear box, while better accelerating units are typically closely spaced, lower ratio gearboxes. For this reason, a balance between acceleration and fuel economy must be found, and priorities must be established.

The optimized gearbox must also remain practical. For example, a gearbox that has inadequate ratio spacing between gears will be unfavorable due to constant shifting. In addition to adding unwanted shifting time during acceleration, frequent shifting deters from the overall driving experience. Although a large ratio gap between 4th and 5th gear may provide desirable low end acceleration and excellent highway fuel economy, too large of a gap will produce drastic acceleration and RPM characteristics between 4th and 5th gear.

**DESCRIPTION OF THE TECHNOLOGY**

The transmission in a manual gearbox automobile serves to facilitate power from the engine to the wheels in an efficient, predictable manner. Using multiple gears, the transmission is able to achieve multiple torque and speed ratios. As the ratio of engine rotation to wheel rotation is decreased, the amount of torque delivered varies inversely.

**Material Selection:**

Materials for production transmissions are fairly standardized, and do not vary across a variety of markets. Typical powertrain packages include a cast aluminum housing and hardened steel gears.

Housing – Cast aluminum with many ribs for strength. Crucial machined features include internal bearing seats, the bell housing mating surface, tapped holes for oil fill and drain, and a speed sensor threaded hole.

Gears – The gears will be machined and hardened steel. Shot peening can be utilized to increase the load carrying capability of the gears without modification to size or geometry. Shot peening a gear provides a work hardened, textured surface which allows tiny relief voids for oil and debris to fill. This reduces stress concentrations on the gear’s contact surface.

Synchronizers – machined brass. The softer characteristics of brass allow the synchronizer to repeatedly contact the steel gears without damaging the gear teeth. These properties also allow the synchronizer to conform to the geometry of the gear fork and any other mating surfaces over time.

Shafts – Shafts are typically steel. Steel lies in the middle ground between lightweight, low strength, and medium cost metals (aluminum alloys) and high strength, high cost, lightweight materials (titanium). Shafts will mate to gears via keyways or machined flats.

**LITERATURE REVIEW**

Currently, the common practice for determining competitor’s material selection and design type is reverse engineering, or benchmarking. This is a simple but costly process, as the competitors product must first be purchased before disassembly and inspection. In general, the materials described above have become quite common for use in manual single-clutch operated gearboxes across a wide range of vehicle applications.

As for the gear ratio optimization program, there are several advanced software packages used in industrial automotive design, such as PSAT (Powertrain Systems Analysis Toolkit). PSAT was created by Argonne National Laboratory, partially funded by the U.S. DOE [1]. Like the MatLab script made during the development of this project, PSAT is also capable of predicted EPA fuel economy, analyzing transmissions, and much more. For the average automotive enthusiast or small company, the downside to this incredibly advanced and robust program is the license cost.

In 2008, after continuous complaints of vehicles that underperformed their EPA rated fuel economy, the EPA made a few key changes to more accurately simulate the modern driving experience. These changes involved additional monitoring of the vehicle at higher speeds, greater accelerations, colder ambient temperature, and while running the vehicle air conditioning system. All of these factors are tested are run independent of each other, and all address modern changes in typical usage that adversely effect fuel economy [2].
OPTIMIZING THE GEARBOX

As previously mentioned, the gear ratios will be optimized based on acceleration and fuel economy criteria. For the purposes of this paper, the following vehicle data will be assumed:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.9</td>
<td>m²</td>
</tr>
<tr>
<td>Cd</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>C_RR</td>
<td>0.0125</td>
<td></td>
</tr>
<tr>
<td>D_eff</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>852</td>
<td>kg</td>
</tr>
<tr>
<td>RPM_{Launch}</td>
<td>4500</td>
<td>rev/minute</td>
</tr>
<tr>
<td>RPM_{Redline}</td>
<td>6000</td>
<td>rev/minute</td>
</tr>
<tr>
<td>Tire_{L, Rad.}</td>
<td>0.292</td>
<td>m</td>
</tr>
<tr>
<td>Tire_{Rev/PerMile}</td>
<td>873</td>
<td>rev/mile</td>
</tr>
</tbody>
</table>

SPEED / ACCELERATION MODEL

The following torque and power curve was assumed for our vehicle. This represents an estimate of a 1.5 liter turbocharged engine conservatively tuned to provide a flat torque line and broad power band.

\[ F_d = \frac{C_d A v^2 + A v^3 \rho}{2} \quad \text{where} \quad v(RPM, GR_i, FD) \]  

\[ T = T_{Launc h \text{ RPM}} \quad \text{for} \quad 0 < RPM < RPM_{Launc h \text{ h}} \]  

This simulated the RPM being held perfectly at RPM_{Launch} while the clutch slipped and the vehicle accelerated from rest. From RPM_{Launch} < RPM < RPM_{Redline}, the clutch was assumed to be fully engaged with no slip, and therefore the RPM and vehicle speed varied linearly in accordance with the gear ratio. This process was only used during 1st gear, as acceleration in all other gears is not from rest.
At all times other than vehicle launch, the maximum torque was known as a direct function of RPM, the acceleration force at any given RPM could be found (Eq. 3).

\[ F_a = T(RPM) * GR_* FD * D_{eff} / Tire_{rad} \]  

(3)

Where \( D_{eff} \) accounts for the rotational friction and inertial losses in the drive train (\( D_{eff} = 0.9 \)). Because our vehicle is assumed to be a transverse mounted mid engine rear wheel drive sports car, there is no intermediate drive shafts or rear differential required to transfer the power to the wheels. For this reason, the assumed drive train efficiency is relatively high compared to most cars.

The rolling resistance force coefficient was assumed to be \( C_{RR} = 0.0125 \). The rolling resistance force was found by the simplified equation for tire rolling resistance (Eq. 4). By summing this force with the force of acceleration and aero drag, the net acceleration can be found (Eq. 5).

\[ F_{RR} = C_{RR} * m * g \]  

(4)

\[ F_{aNet} = F_a - F_{RR} - F_d \]  

(5)

Because the vehicle mass is known, the acceleration can be found by Eq. 6.

\[ A_{Net} = F_{aNet} / m \]  

(6)

By manipulating the physics relation \( A = dv / dt \), the time needed to accelerate to a 60 mph (26.8 m/s) can be found using Eq. 7.

\[ t_{0-60} = \int_0^{60} \frac{1}{A_{Net}} dv \]  

(7)

Where \( A_{Net} \) is a function of RPM, \( GR_* \) and FD. In order to integrate \( A_{Net} \) with respect to speed, speed must be calculated given the selected gear and RPM.

Using the relation in Eq. 7 in conjunction with the process described by Eq. 2 and Eq. 3, the cumulative time it takes to accelerate to any speed was found by numerically integrating Eq. 7 using the trapezoidal rule with a velocity increment of 0.01 m/s. Because the torque changes based on gear ratio, a loop was run for each gear, and the torque equation was updated with the new gear ratio in accordance with vehicle shift points.

A user shift time (\( t_{shift} \)) of 0.2 seconds was also assigned. During each gear change, the \( t_{shift} \) was added to the cumulative time to account for the time the driver would take to shift the car. The speed was assumed to remain constant during this time.

Similarly, the time needed to accelerate to 100 mph (44.7 m/s) was found using (Eq. 8).

\[ t_{0-100} = \int_0^{100} \frac{1}{A_{Net}} dv \]  

(8)

This model proved to be fairly consistent, and provided a convergence of 4 decimal places when calculating 0-60 and 0-100 acceleration times using the 0.01 m/s numerical integration increment.

After completing the iterations, the script returns \( t_{0-60} \), \( t_{0-100} \), and the gear at which each speed was achieved in.

**EPA FUEL ESTIMATE MODEL**

In order to estimate the fuel economy of the vehicle, the following engine data was taken from a typical 1.5 liter engine (Figure 3).

<table>
<thead>
<tr>
<th>Torque (N-m)</th>
<th>Fuel Consumption kg/s (1x10^-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.8</td>
<td>0.10</td>
</tr>
<tr>
<td>15.2</td>
<td>0.13</td>
</tr>
<tr>
<td>22.8</td>
<td>0.18</td>
</tr>
<tr>
<td>30.2</td>
<td>0.19</td>
</tr>
<tr>
<td>37.8</td>
<td>0.21</td>
</tr>
<tr>
<td>45.4</td>
<td>0.24</td>
</tr>
<tr>
<td>53.0</td>
<td>0.27</td>
</tr>
<tr>
<td>60.6</td>
<td>0.31</td>
</tr>
<tr>
<td>68.2</td>
<td>0.36</td>
</tr>
<tr>
<td>75.7</td>
<td>0.39</td>
</tr>
<tr>
<td>83.3</td>
<td>0.40</td>
</tr>
<tr>
<td>90.9</td>
<td>0.44</td>
</tr>
</tbody>
</table>

In order to code this table into an iteratively run program, it was convenient to fit a surface and polynomial equation to the table. This way the program could find a fuel usage rate given a certain RPM and Torque value. The surface was fit using a 21 degree of freedom polynomial surface (Figure 4).

![Figure 3. Fuel Usage vs. Engine Speed & Torque.](image-url)

![Figure 4. Fuel Usage Surface Fit](image-url)
The fuel economy was analyzed by running a code to simulate the vehicle driving through 3 of the EPA’s standardized tests; City, Highway, and Highspeed.

**CITY FUEL ECONOMY**
The EPA provides the following information about their city fuel economy test (Figure 5) [2].

![Figure 5. EPA City Fuel Economy Cycle](image)

In order to simplify the simulation for the city fuel economy, the driving conditions seen in Figure 5 were estimated using the following:

<table>
<thead>
<tr>
<th>Number of Runs</th>
<th>Description</th>
<th>Rate of Acceleration</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0-30 mph burst (0-13.4 m/s)</td>
<td>3.3 mph/s (1.47 m/s²)</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0-57 mph burst (0-25.5 m/s)</td>
<td>3.3 mph/s (1.47 m/s²)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>35 mph cruise (15.6 m/s)</td>
<td>-</td>
<td>8 minutes</td>
</tr>
<tr>
<td>1</td>
<td>53 mph cruise (23.7 m/s)</td>
<td>-</td>
<td>6 minutes</td>
</tr>
</tbody>
</table>

**Table 1. City EPA Test Estimates**

**HIGHWAY FUEL ECONOMY**
The EPA provides the following information about their highway fuel economy test (Figure 6) [2].

![Figure 6. EPA Highway Fuel Economy Cycle](image)

In order to simplify the simulation for the city fuel economy, the driving conditions seen in Figure 6 were estimated using the following:

<table>
<thead>
<tr>
<th>Number of Runs</th>
<th>Description</th>
<th>Rate of Acceleration</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0-40 mph burst (0-17.9 m/s)</td>
<td>3.2 mph/s (1.43 m/s²)</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>35-60 mph burst (15.6-26.8 m/s)</td>
<td>3.2 mph/s (1.43 m/s²)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>35 mph cruise (15.6 m/s)</td>
<td>-</td>
<td>6 minutes</td>
</tr>
<tr>
<td>1</td>
<td>53 mph cruise (25.0 m/s)</td>
<td>-</td>
<td>12 minutes</td>
</tr>
</tbody>
</table>

**Table 2. Highway EPA Test Estimates**

**HIGHWAY FUEL ECONOMY**
The EPA provides the following information about their highway fuel economy test (Figure 7) [2].

![Figure 7. EPA Highway Fuel Economy Cycle](image)

In order to simplify the simulation for the city fuel economy, the driving conditions seen in Figure 7 were estimated using the following:

<table>
<thead>
<tr>
<th>Number of Runs</th>
<th>Description</th>
<th>Rate of Acceleration</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0-75 mph burst (0-33.5 m/s)</td>
<td>Maximum Acceleration</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>0-40 mph burst (0-17.9 m/s)</td>
<td>Maximum Acceleration</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>60 mph cruise (26.8 m/s)</td>
<td>-</td>
<td>5 minutes</td>
</tr>
<tr>
<td>1</td>
<td>80 mph cruise (35.7 m/s)</td>
<td>-</td>
<td>5 minutes</td>
</tr>
</tbody>
</table>

**Table 3. Highspeed EPA Test Estimates**

**CODE GUIDELINES**
The following limits were set on each of the tests to assist the simulation program in selecting an appropriate gear. The limits were chosen to characterize the driving style described by the rates of acceleration and speeds during each test.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>City Accelerating Shift RPM</td>
<td>4500</td>
</tr>
<tr>
<td>City Max Cruise RPM</td>
<td>3450</td>
</tr>
<tr>
<td>Highway Accelerating Shift RPM</td>
<td>4500</td>
</tr>
<tr>
<td>Highway Max Cruise RPM</td>
<td>3300</td>
</tr>
<tr>
<td>Highspeed Accelerating Shift RPM</td>
<td>5500</td>
</tr>
<tr>
<td>Highspeed Max Cruise RPM</td>
<td>3950</td>
</tr>
</tbody>
</table>

**Table 4. RPM Limits for each simulation**
The air conditioning and cold temperature tests were neglected because there was no engine data available for operating in these conditions. However, because this is a transmission gear ratio optimization exercise, the effects of operating at different coolant temperatures and while using air conditioning are irrelevant as they would affect every gear ratio set in the same manner.

The vehicle event estimates chosen for each test only calculate fuel used and distance traveled while accelerating or cruising. In a real driving situation, the vehicle would also travel a certain distance while braking or coasting to a stop. During this brake/coast event, the engine would likely be at idle. Therefore, a certain amount of distance and fuel could be added to the cumulative total to account for this event. This was not done because the distance traveled and fuel used during this braking/coasting event would be the same regardless of the gear ratio, and would therefore not affect the optimization routine or result of this project.

**CODE PROCEDURE**

As shown in Tables 1-3, the city, highway, and highspeed tests are all simulated by 2 classes of acceleration events and 2 classes of cruising events.

During the constant acceleration events, the torque required is derived from the amount of force required to accelerate at the required rate and overcome rolling resistance, aero drag, and drive train efficiency losses.

During the highspeed maximum acceleration events, the torque is set equal to the maximum torque available based on RPM, and the resulting acceleration is determined after subtracting the rolling resistance, aero drag, and drive train efficiency losses.

During the cruising events, there is no acceleration, and therefore the only torque required is the amount necessary to overcome aero drag, rolling resistance, and drive train losses.

To calculate the amount of fuel used during a driving event, the simulation script first determines the instantaneous speed, RPM, and torque requirements of the engine. The program then uses the surface fit equation to find the fuel usage (kg per second) at this instant, and multiplies this by a time increment of 0.01 seconds to find the fuel used (in kg) during the time interval. The speed is then updated by multiplying the instantaneous acceleration by the time interval (0.01 seconds) and adding this increase to the current speed. Based on this updated speed, the RPM is recalculated, and a gear shift occurs if the RPM has exceeded the target based on Table 4. A cumulative fuel variable is used to keep track of the fuel used throughout the driving event.

In acceleration (burst) events, the loop ends when the target velocity has been reached. In cruise events, the loop ends when the required amount of time has passed. At this time, the cumulative fuel used during the event is divided by the total distance traveled during the event to find the average fuel economy for that event.

This process is used for the events in the city, highway, and highspeed EPA tests in accordance with Tables 1-4. At the end of the program, the script returns the EPA fuel mileage estimate for city, highway, and highspeed driving, as well as average fuel economy over all three tests.

**DISCUSSION**

Overall, the code proved to provide an effective measure of performance based on the design priorities:

- a) Vehicle 0-60 mph time
- b) Vehicle 0-100 mph time
- c) Fuel economy during a standardized EPA test

Possible refinements for the code would include a more advanced simulation of tire rolling resistance, a more accurate polynomial surface fit to the fuel usage table, and more engine data to model operating under different conditions (varying ambient temperatures, varying coolant temperatures, air conditioning on, etc.).

With these improvements in place, this code could serve as a more affordable substitute to the PSAT or other vehicle simulation software. Alternatively, this code could be used to find major design errors before spending the money on a more refined model such as PSAT.

**CONCLUSIONS AND RECOMMENDATIONS**

This project provided me with a code that will be useful in the future and the following results for an optimized gearset:

<table>
<thead>
<tr>
<th></th>
<th>Time (seconds)</th>
<th>Fuel Economy (mpg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-60</td>
<td>9.03</td>
<td>City 67.08</td>
</tr>
<tr>
<td>0-100</td>
<td>29.6</td>
<td>Highway 70.54</td>
</tr>
<tr>
<td>City</td>
<td></td>
<td>Highspeed 43.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average 60.53</td>
</tr>
</tbody>
</table>

**REFERENCES**
[1] Rousseau, A. "POWERTRAIN SYSTEMS ANALYSIS TOOLKIT (PSAT)
A Flexible, Reusable Model for Simulating Advanced Vehicles

ACKNOWLEDGMENTS

Special thanks to Chris Auerbach