Drive System Mechanics for Electric Drive Conversion of a Lotus Elise

The REV Project

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1. Project Summary

The REV group seeks to design and build and electrically driven conversion of the Lotus Elise sports car. The overall goals are to raise public awareness and education of electric vehicles as an alternative form of everyday transportation as well as a competitive race platform. This report describes the design and layout of the drive system mechanics of the proposed vehicle. The goals of this project are threefold:

- Investigate available options for gearing the chosen electric motor and decide upon the most appropriate solution
- Work with other members of the mechanical group to successfully incorporate all elements of the overall design into the available design space
- Design the parts necessary to connect the elements of the drivetrain to one another and to the frame of the vehicle

Choosing an appropriate method of gearing the motor has been done using performance modeling of vehicle acceleration and tops speed as well as spatial modeling of relevant components within the body of the vehicle. The chosen design is to reuse the original PG1 Gearbox found in the Lotus. This will allow flexibility in vehicle acceleration and top speed, but restrict space available for other components and negatively affect the loading on the rear axle. This design was chosen because all other proposed solutions violated fundamental design constraints. A general layout of components was decided upon within the group and designs were completed that provide a method of securely mounting and connecting the motor and gearbox inside the engine compartment.

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2. Introduction

The purpose of this project has been to design the drive system for a Lotus Elise that is to be converted from a petrol powered automobile to an electric powered one. This work is being done by the REV (Renewable Energy Vehicle) team at the University of Western Australia. The scope of this particular project includes the selection of a gearing method and the design of the spatial arrangement and mechanical supports of the various drivetrain components in the engine compartment. The electric motor and controller as well as the specific batteries were chosen prior, so their selection is not within the scope of this project. Battery housing, suspension augmentation, motor cooling, and performance modeling are also outside the range of this project as they will be dealt with by other members of the REV team. However, their work will be referred to frequently throughout this report.

2.1. The Renewable Energy Vehicle Team

The REV team is a multidisciplinary group led by Dr. Thomas Braunl of the School of Electrical Engineering in conjunction with Kamy Cheng of the School of Mechanical Engineering. Engineers on the team were broken down into smaller groups by discipline of study. For example this project was done as a part of the mechanical group, composed of six mechanical engineers. Groups communicate progress in interrelated material to one another at weekly meetings. In regard to the Lotus conversion, the progress of other groups is largely dependent on the completion of the majority of the mechanical group's work. Individual projects within the mechanical group have also proven to be highly interrelated. Team members must communicate with one another in order to ensure that all the individual components can be successfully arranged within the vehicle and that no single design jeopardizes the success of any other. Knowing these logistics will prove useful in explaining design objectives and constraints.

2.2. History and State of the Art

The electric car is not a new idea. They existed before the introduction of the Ford Model T, but have never gained popularity because of a number of economic, political, and technical factors. The story of GM's EV1 electric vehicle is an example of how these different factors have affected the failure of electric cars in reaching mainstream appeal (Paine 2006). Recent developments in the past few years have led to renewed interest in the development of electric automobiles for mass consumption. These developments include recent volatility in the price of oil, a desire for national energy independence, raised awareness of global climate change, and advances in battery technology (Mathew 2008). As a result progress towards the development of electric vehicles has been widely publicized, as seen with the Tesla Roadster, BYD's e6, and the Chevy Volt.

All of these projects have run into problems, however. Tesla has struggled with vehicle handling due to the added weight of its lithium-polymer batteries. It has also failed to design a gearbox that is compatible with the car's large electric motor, resorting instead to a single-speed differential. China's BYD has successfully built an affordable electric vehicle, the e6, but vehicle safety concerns will most likely prevent its export into developed countries (Filliponio 2009). Chevy announced the Volt in 2007, but struggled to affordably build the promised plug-in hybrid vehicle that can function as an electric vehicle for a short period of time (Tate 2008). The REV project has attempted to learn from these well publicized endeavors, but due primarily to limited resources has run into many of the same issues.

Over the course of the past academic year, the REV team was successful in converting a Hyundai Getz into a fully electric vehicle (Mathew 2008). This endeavor has provided insight and experience to the current Lotus project. Methods and designs used in the Getz will be referred to in this report. Of particular use were the designs for connecting an electric motor to the original gearbox in the Getz, as the final design in the Lotus proved to be similar (Tan 2008).

The conversion of the Lotus Elise will ideally advance the state of the art of electric cars within the REV Project, Western Australia, and Australia as a whole. The aim is to produce an electric vehicle with comparable performance characteristics to the original Lotus Elise, while retaining a practical driving range. All of this is done relatively affordably using parts available to the general public. One of the original goals of the REV project is to "increase public awareness of electric vehicles as an alternative means of transportation", which can be achieved through the natural appeal of a sports cars (Mathew 2008).

2.3. Drive System Mechanics

The Lotus Elise is a popular sports car, known for its small size and excellent handling characteristics. The mechanical group of the REV team seeks to produce an electric conversion of the Elise that proves to be just as nimble. This involves minimizing added weight, retaining cornering profile, and preserving or improving acceleration performance. All of these larger goals are relevant to the specific design project described below, the drive system mechanics of the Lotus Elise conversion.

Figure 1: 2002 Lotus Elise Purchased for REV Project[1]

As the electric motor has already been chosen[2], the goals of the project are listed in the table below:

Project Goals
1. Investigate available options for gearing the chosen electric motor and decide upon the most appropriate solution
2. Work with other members of the mechanical group to successfully incorporate all elements of overall design into available space
3. Design the parts necessary to connect the elements of the drivetrain to one another and to the frame of the vehicle.

Figure 2: Table of Project Goals

[1] Image courtesy of Stephen Whitely
[2] See Appendix I

The goals were pursued in this order, keeping in mind subsequent ones so as not to prevent their success. The specific objectives and constraints of each goal are listed in the following sections, but a general understanding is given below.

There are a number of options available for gearing the electric motor. These include reusing the original Lotus gearbox, purchasing a new gearbox, or using a single-speed differential. Each option carries advantages and disadvantages in balancing top speed, acceleration, weight distribution, part availability, cost, and utilization of available space. Steps towards achieving this goal involve an extensive search of available parts and performance modeling of the vehicle with different gearing options.

The second goal is accomplished through extensive communication and design revision with members of the mechanical group. The placement of many components such as batteries and coolant pump is dependent on the final design of the gearing. Once the first goal had been accomplished, the team was able to determine the location of the remaining necessary components through a number of revisions to the original layout.

The third goal is mounting of the gearbox (or differential) and motor. With the overall layout decided, mounting points and structures can be shared between components in order to optimize spatial use and minimize clutter and weight. This was done through group communication and parallel design processes between group members.

2.4. <u>Background: Relevant Automotive Parts</u>

This section gives a short background of automotive parts relevant to this project. An overall layout of the connection order of the parts is given below in Figure 3.

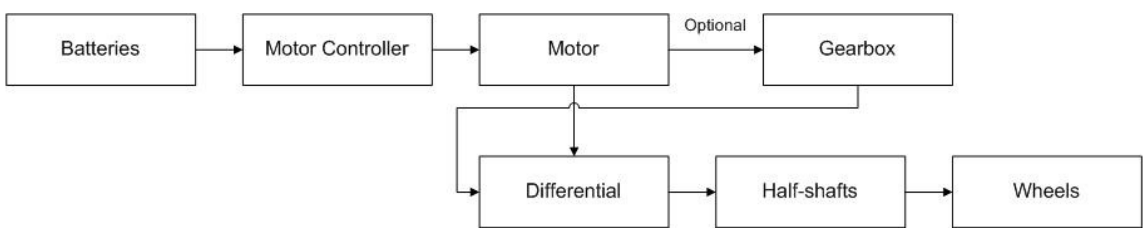

Figure 3: Power Transfer in Proposed Drivetrain

Electric Motor – The most obvious difference between an electric and an internal combustion motor is that an electric motor converts electrical energy into motion, while an internal combustion energy converts chemical energy into motion. Electric motors operate at a much higher efficiency (90-95%) than an internal combustion engine (~40%). Electric motors also tend to produce higher torque at lower rpms than an internal combustion engine. The particular motor chosen for this project is powered by a controller, both of which are liquid cooled, which distributes power from the battery pack to the motor. Further information is located in Appendix I.

Gearbox – A gearbox is a complex device that acts as a torque multiplier between the motor and the wheels. This project deals solely with standard (or manual) gearboxes as automation adds a further level of complexity. A modern gearbox usually has five or six gears plus reverse, while older models tend to have fewer. For a given gear, with gear ratio X, the gearbox serves to multiply the output torque of the motor by X, while multiplying the output motor speed by $1/X$. This tradeoff between speed and torque is optimized over a number of gears to produce a balance of acceleration and speed. A gearbox contains within it a differential, which is described in further detail below. A diagram is shown below in Figure 4. Further details on the specific gearbox found in the Lotus Elise are included in Appendix II.

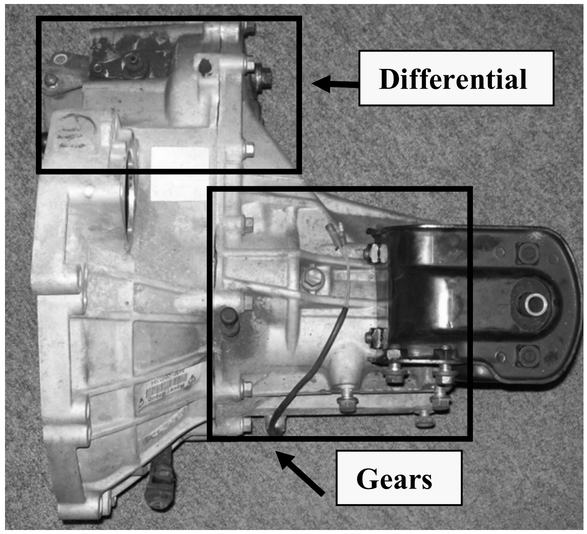

Figure 4: Lotus Elise Original Transmission

Differential – In order for a vehicle to turn, the inside and outside wheels must move at a different rate to prevent them from slipping. A differential is a mechanical device allows this to occur, despite the fact that both wheel are attached to the same motor (Handy 1937). Additionally, a differential is characterized by an overall gear ratio, similar to a gearbox, except that it is a fixed value. This is referred to as a final ratio. In order to get the overall gear ratio between the motor and the wheels in any given gear, the ratio of the gearbox gear must be multiplied by the ratio of the differential. The Tesla Roadster eliminates the gearbox and only uses a differential, which limits the vehicle to one gear.

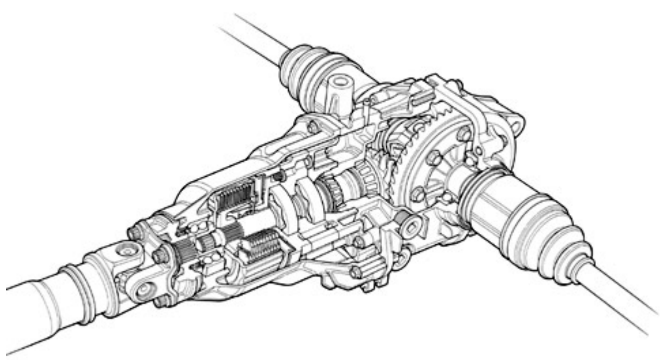

Figure 5: Internal View of Differential

Half-shafts – A half-shaft refers to the rotating shaft that connects the differential to the wheels. This is not to be confused with a drive shaft, which connects the gearbox to the rear differential in rear wheel or all wheel drive vehicles. In vehicles with independent suspension on the driving wheels, such as the Lotus, the half-shafts are self-supporting and contain two universal joints so that the wheels can move while the differential remains stationary. This setup is shown in Figure 6. In vehicles with a solid rear axle, such as trucks, the half-shafts are contained within an axle housing and the rear differential moves with the rear wheels.

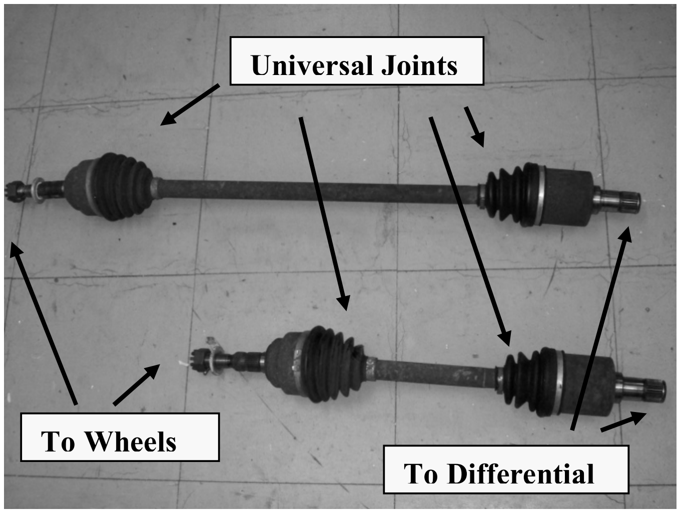

Figure 6: Half-shafts from Lotus Elise

Motor Mounts – An internal combustion engine produces constant vibration that unless otherwise compensated for, would be transferred directly into the frame of the car. This would cause discomfort for the driver and fatigue in parts throughout the vehicle. In order to isolate this vibration, rubber joints are used to mount the motor, which dampen this vibration. They also serve to isolate the motor and gearbox from the stresses placed on the frame of the car during use.


Figure 7: Rubber Motor Mount from Lotus Elise

2.5. <u>Overview</u>

The report will focus on goal 1) from Figure 2 and the associated design process. The following section will detail the design approach including objectives, constraints, and modeling techniques used in choosing an optimal solution for the motor gearing. The subsequent section will outline the specific design alternatives that were developed including advantages and disadvantages of each. The results section will focus on which design alternative was chosen and the justification for its choosing. The repercussions of this choice will be briefly discussed in relation to goal 2). Next the resulting design for the motor and gearbox supports will be discussed as outlined in goal 3). Finally conclusions about the feasibility of the final design will be drawn and recommendations will be made for future work.

3. Design Approach

In order to choose a "best" design solution that satisfies the first goal of this project (Figure 2), a number of measures were taken to rate possible designs in the context of the outlined problem. The most obvious way of creating a system to compare design solutions is by outlining a number of objectives and constraints that can be used to judge design alternatives. These are listed in Figure 8 and described in detail below.

Objectives	Constraints
Design alternatives should seek to:	***Viable designs must:***
1) Maximize benchmark acceleration times	**1) Have a minimum top speed of 160 km/hr**
2) Maximize leftover space in engine compartment	**2) Be compatible with existing independent suspension**
3) Minimize load on rear axle	**3) Have parts readily available**
4) Minimize cost	**4) Not jeopardize the objectives of other group members**
5) Minimize construction time/labor	**5) Fit into Lotus' design space without major modifications to the vehicle**
	6) Must be rated to handle output torque of electric motor

Figure 8: Objectives and Constraints for Motor Gearing Design

3.1. Objectives

Maximize benchmark acceleration times – The purpose of converting a sports car such as the Lotus Elise was to prove that electric cars can compete with both commuter and high performance automobiles. In order for the electric Lotus Elise to be a respectable high performance vehicle, the car must be able to produce competitive acceleration times. A model for vehicle performance, produced by Frans Ho for his final year project, will be used to predict acceleration times for specific gearing solutions. This model will be explained in further detail later. Benchmark acceleration times of 0-60 km/hr and 0-100 km/hr will be used for comparison.

Maximize leftover space in engine compartment – The design space allocated to the mechanical group has proven to be rather limited, considering the number of components that are required to fit in the space. In addition to the engine compartment, the space under the boot where the exhaust system was originally, as well as the boot itself can be used to place components. Ideally, all components would be placed in the original engine compartment, as this would optimize weight distribution and access. Other components that are competing for space with the motor and gearbox/differential include 100 lithium-phosphate batteries, the motor controller, a battery charger, a coolant pump, the original computer, and other electronics. The less space that the drivetrain takes up, the easier it will be for other members of the group to complete their projects.

Minimize load on rear axle[3] – It is inevitable that more weight will be added to the vehicle to convert it to an electric drive, than was removed. As a result, the axle loading and handling characteristics of the vehicle will inevitably change. Most of the added weight will be located in the rear half of the vehicle. In an effort to minimize rear axle loading, and consequently suspension redesign, an effort has been made to place as many of the components as far forward in the vehicle as possible.

Minimize cost – While seemingly obvious, an effort has been made to minimize the construction cost of the vehicle. In this sense less costly solutions will be weighted higher than more expensive solutions of the same utility.

Minimize construction time/labor – Due to a number of factors, resources in the electrical engineering workshop have been limited over the course of the semester. As a result, components that need to be manufactured will be designed to reduce construction time and cost. In other words simpler solutions will be weighted higher than more complicated and labor intensive ones.

3.2. Constraints

Have a minimum top speed of 160 km/hr – A consensus was made that the minimum allowable top speed for the vehicle would be 160 km/hr. This was due to a number of factors including track tests that were conducted on the Lotus prior to electric conversion. In most designs, a trade-off has been made between acceleration times and top speeds and this constraint pegs the top speed in order to more effectively optimize acceleration profiles.

Be compatible with existing independent suspension – The Lotus Elise has an independent rear suspension, which means that the rear wheels move independently of one another. Any gearbox or differential that is chosen cannot compromise this fundamental element of the car's design. In other words, the gearbox or differential that is chosen must have originally come from or have been designed for a vehicle with independent rear suspension. Trucks, for example, do not have independent rear suspensions, so a truck differential would most likely not be compatible for use in the Lotus conversion.

Not jeopardize the objectives of other group members – Any design decision made by any group member must not jeopardize the fundamental objectives of any other group member's project. For example, a design that places the gearbox and motor in the engine compartment must leave sufficient room for battery cages and other necessary components.

Fit into Lotus' design space without major modifications to vehicle – As a result of the limited labor and construction time that can be put into the project, any design that requires major modifications to the vehicle structure is deemed unacceptable. In particular the rear sub frame shown in Figure 10 creates a limiting dimension in many design alternatives. Any modification to this structure is deemed unfeasible.

Must be rated to handle output torque of electric motor – The maximum output torque of the motor is 240 Nm. Any differential or gearbox that is chosen must be rated as being able to handle this torque. For example, original gearbox in the Lotus has been rated to handle exactly 240 Nm of torque (Powertrainltd).

[3] For all data pertaining to rear axle loading, see the third year report produced by Caleb Tang.

3.3. Performance Modeling

In order to rank design alternatives in relation to the first objective (Figure 8), a method of predicting vehicle performance was developed. A computational model was developed by Frans Ho for his final year project that uses a number of vehicle, motor, and gearing variables to predict the acceleration times, top speed, and ideal gearing ratios for a given setup. A flow chart describing the functions and method of the model is shown in Figure 9.

The model uses the motor torque curve and gear ratios to determine the torque at the wheels in any given gear and at a specific rotational speed. Then the amount of torque that is used up with aerodynamic drag and road friction is subtracted out. Approximated drivetrain efficiency is also taken into account. Using the wheel profile, the maximum rotational speed of the motor, the vehicle weight, and the calculated wheel torque, the acceleration profile of the vehicle can be calculated based on a specific setup. From this acceleration profile, the maximum speed of the vehicle and benchmark accelerations can be determined. In addition, the model was used to optimize the gear ratio for design alternatives using a differential instead of a gearbox. It was also used to determine which gears in the existing gearbox would produce the best results, as all five gears are unnecessary with the torque curve of an electric motor.

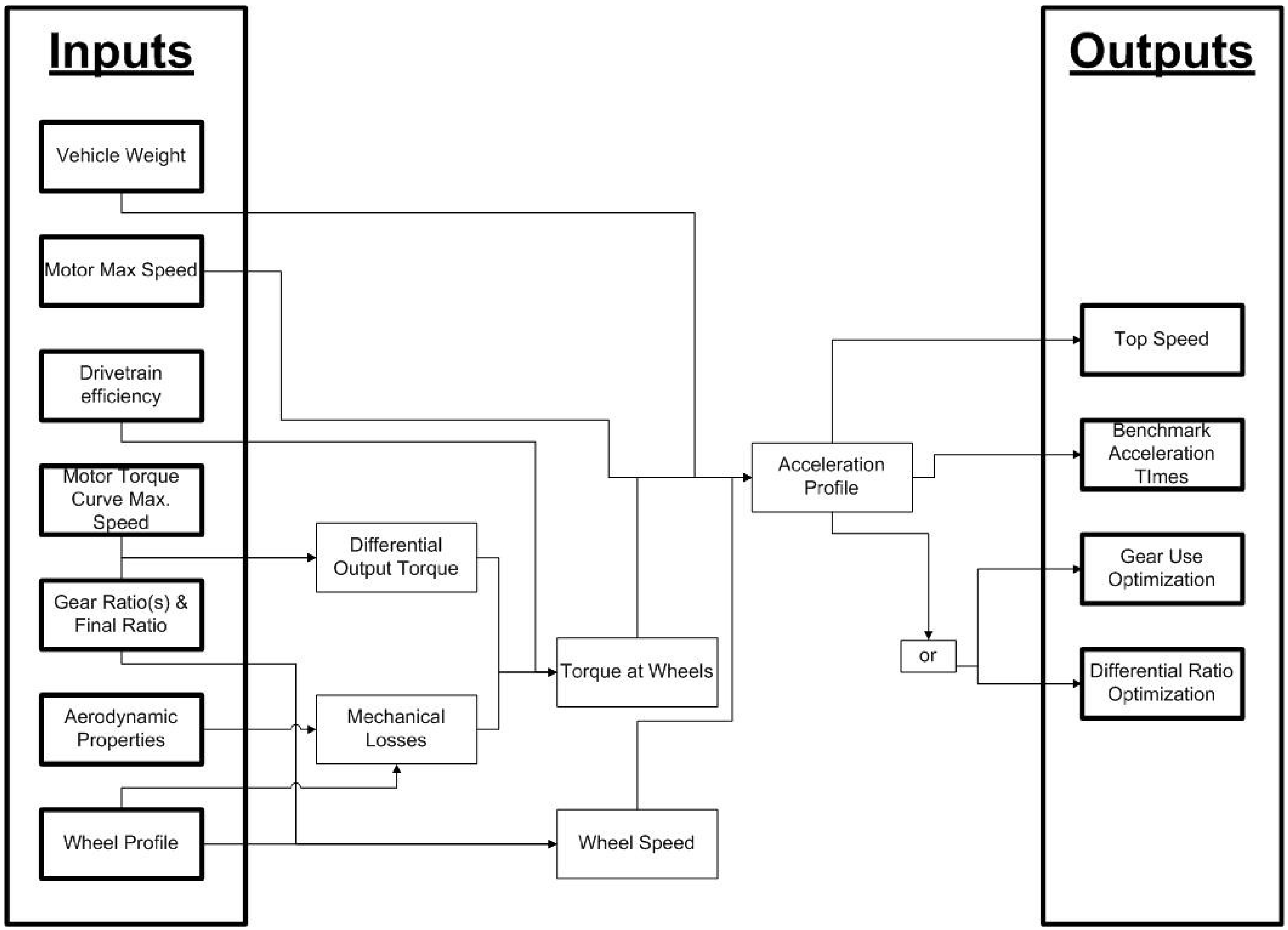

Figure 9: Computational method of Frans Ho's performance model.

3.4. Spatial Modeling

The 2nd objective and the 4th and 5th constraints (Figure 8) of this design project all deal with the use of space in relation to other members of the mechanical group. Many systems designed by members of the group must all share the same space within the vehicle's engine compartment and other available spaces. Some parts must even be designed with sufficient precision to connect to those designed by other team members. In order to facilitate this level of communication and organization, SolidWorks 3D modeling software was utilized to insure that all necessary components could fit in the required space. The basic model of the engine compartment and rear section of the car is shown below.

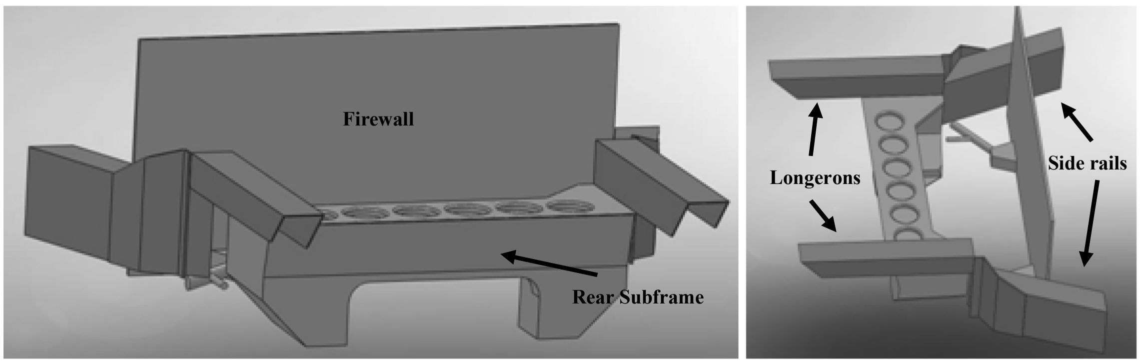

Figure 10: SolidWorks - Engine Compartment

The space available to this project is the engine compartment (the space defined by the rear subframe , the side rails, and the firewall), the area located underneath the longerons (where the exhaust system used to be), and the fuel tank area behind the firewall. The SolidWorks modeling allows group members to view their components in relation to one another and in relation to the vehicle structure. It has helped to create a dynamic design process within the group and has reduced frustration and continuous measurements when considering design alternatives.

4. Design Alternatives

This section outlines a number of design alternatives that were considered as possible solutions for the gearing of the electric motor. Each alternative is described in relation to the objectives and constraints. Visual representations are given where possible. The two broadest categories of solution are those that solely use a differential and those that use a gearbox. Different types of gearboxes and differential are described as possible solutions.

4.1. Retaining Original Gearbox

The most obvious solution and possibly easiest way to gear the electric motor would be to use the original gearbox that was in the Lotus. By leaving the gearbox in place, no major parts would need to be purchased and the original half-shafts could be used with no modifications. Also, multiple gears give flexibility in creating several acceleration profiles and top speeds, depending on the chosen gear. This is the same solution that was decided upon in the Getz last year, so the basic procedure of mounting the motor and gearbox had already been figured out (Tan 2008). The primary disadvantage of using the original gearbox is the space that it takes up in the engine compartment. If the gearbox is left in its original location, the motor and gearbox (shown in Figure 11) will only leave half of the engine compartment for batteries, forcing the remainder behind the rear wheels. This negatively affects the loading on the rear axle.

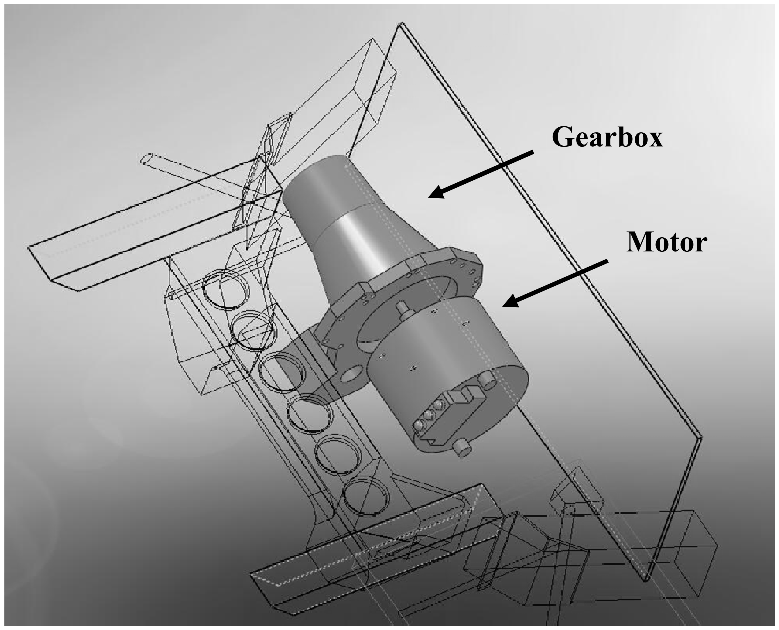

Figure 11: Original Gearbox and Motor in Engine Compartment

Another consideration in this design is whether or not to keep the clutch, and consequently the flywheel, or to remove them completely. Figure 11 shows the assembly with the clutch removed. While the gearbox is rated to handle the increased torque produced by the electric motor, it is inevitable that this would “burn up” the clutch relatively quickly since maximum torque is produced at low engine speeds. The particular gearbox is not found in many common vehicles and therefore custom clutches built for higher torque are difficult to find. A high performance clutch and flywheel normally cost around $500 USD each. Furthermore, building housings for the clutch and flywheel would be labor intensive and would take up further room in the engine compartment. On the other hand, removing the clutch would make quick gear shifting difficult in race conditions.

4.2. Purchasing a New Gearbox

The large size of the original gearbox is its largest drawback. It fills much of the engine compartment, which should ideally be used for battery storage. One way to retain the flexibility of multiple gears, while freeing up space in the engine compartment is replacing the existing gearbox with one from a rear-engine vehicle. A rear engine vehicle’s transmission is designed so that the attached motor is perpendicular to the vehicle’s half-shafts. If this setup were used in the Lotus, it would allow the motor to be removed completely from the engine compartment. Instead the gearbox would be placed underneath the rear subframe and the motor would be placed underneath the boot, where the exhaust system was originally. This would allow the entire battery array to be placed in front of the rear axle, minimizing the loading on that axle. Only a small portion of the engine compartment would be taken up by the gearbox. The setup, along with a sketch of this type of transmission is shown in Figure 12.

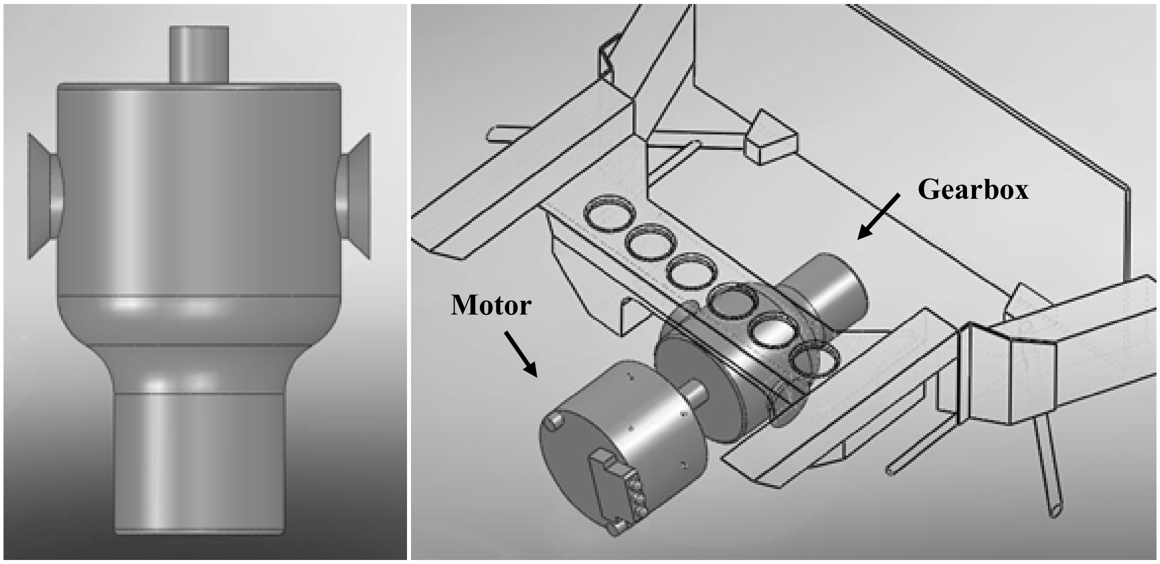

Figure 12: Rear-engine Gearbox (sketch) and Possible Drivetrain Design

The first problem with this design is the difficulty in acquiring this particular type of transmission. The rear-engine vehicle was largely discontinued in the 1980s and most of these vehicles were small economy cars. The gearboxes in these cars are not rated for the high torque output of the electric motor. One of the few cars with a sufficiently robust transmission was the late model Renault Fuego, which was imported in limited numbers into Australia (Chapman 2007). It is arguable that even this transmission wouldn't be able to handle the torque. The group was unable to locate the transmission from one of these vehicles at the local wreckers. Instead it would have to be ordered internationally or the entire vehicle would have to be purchased for the transmission. This would cost roughly $2200 AUD and would most likely produce a well-worn transmission.

4.3. Choosing the Correct Differential

From a mechanical perspective, the simplest solution would be to replace the gearbox with a differential, leaving a single gear ratio between the motor and wheels. This reduction has a number of advantages and disadvantages. The first advantage is that a differential can easily withstand the torque output of the motor, as they are usually placed after a gearbox, which serves as a torque multiplier. The second advantage is that is that a differential would take up no room in the engine compartment, and like the rear-engine transmission setup; the motor would be located behind the engine compartment. Again this ideally would minimize the rear axle loading by transferring more battery weight towards the front of the vehicle. A diagram of this specific setup is shown below in Figure 13.

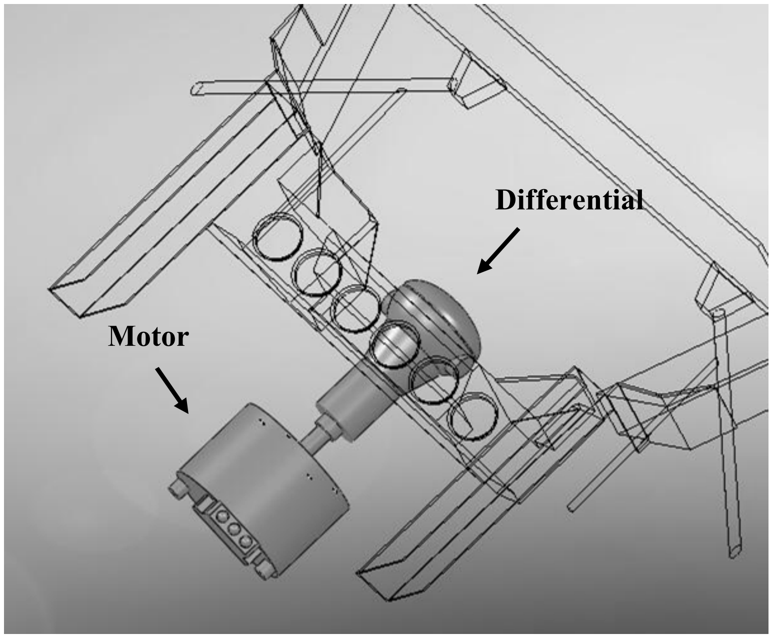

Figure 13: Differential and Motor Design Alternative

This design has a number of disadvantages; however. The first is obvious looking at Figure 13. The differential in the figure is modeled after a 7.5” Toyota differential, which is a relatively small differential. Even so, the motor is forced so far towards the rear of the car by the dimensions of the differential that it is close to touching the rear of the clam shell (Toyota 7.5”). Cantilevering the motor this far from the rear axle produces two problems. First is the physical difficulty of mounting the motor in this position and second is that this actually increases the load on the rear axle, even though the heavier batteries are in the engine compartment.

The second major disadvantage is acquiring a differential with the correct gear ratio. The performance model predicted that for the electric motor, the ideal gear ratio would be 6.0:1. A lower gear ratio would produce slower acceleration times and a higher ratio would limit the top speed of the car to under the required 160 km/hr. This ratio is higher than is found in commercial vehicles. Standard passenger cars tend not to have a rear differential, but if they do, the ratio tends to be approximately 4:1. Trucks and four-wheel drive vehicles can have higher ratios, but also have a solid rear axle. As discussed earlier, a differential built for a solid rear axle is not compatible with the independent suspension in the Lotus. The best solution found so far is the 7.5” Toyota differential (modeled above) that has been modified for use in a Daihatsu Terios 7-seater. This model has a gear ratio of 5.71:1 and has been altered to be compatible with the independent suspension in the Terios (Terios 7 seater 2008). If used, the Terios’ half-shafts would need to be purchased as well, cut, and welded to the original half-shafts. This way the new hybrid shafts have one end that mates to the new differential and another end that can mate to the wheels. This differential still suffers the size problems mentioned above.

4.4. Other Differential Options

Other options include having a differential custom made or purchasing a usable differential with a low gear ratio. Custom differential are primarily for four-wheel drive or hot-rod applications, meaning that they are for vehicles with solid rear axles and very high power (~350kW). As a result they tend to be much larger than the differential shown in Figure 13. It is possible to change the gear ratio in a given differential, so if a differential of the correct size were found, there is a chance that parts exist to change the gear ratio to a desired value. This is done by replacing the ring and pinion inside the differential housing. There has been little success finding a differential of the correct size with the correctly sized ring and pinion available for purchase.

Figure 14: Ring and Pinion from a Differential

5. Results

With the details of the various design alternatives laid out, they can be compared and an optimal solution can be decided upon. This process first involves determining which of the designs violate constraints. If a design violates a constraint then it is not viable and is thrown out. The designs that don't violate constraints will then be compared in terms of their performance with respect to the design objectives.

5.1. <u>Constraint Analysis</u>

The first step is to determine which of the possible designs violate any of the constraints laid out in Figure 8. The following table lists each design alternative and each constraint. If a given design violates a constraint, the box is black, and if it is only a possibility that a constraint is violated the box is shaded. Otherwise, the corresponding box will be left white.

Design Alternative	1) Have a minimum top speed of 160 km/hr	2) Be compatible with existing independent suspension	3) Have parts readily available	4) Not jeopardize the objectives of other group members	5) Fit into Lotus' design space without major modifications to vehicle	6) Must be rated to handle output torque of electric motor
A. Existing Gearbox w/clutch			Clutch and flywheel needed			
B. Existing Gearbox w/o clutch				Very difficult to accommod-ate all 100 batteries		
C. Rear-engine Gearbox			Gearbox not located			No concrete data, only estimates
D. Truck Differential		Designed for solid rear axle			Too large	
E. Daihatsu Terios Differential			Must be ordered from Japan			
F. Custom Differential		Usually built for solid rear axle	Must be ordered from the US		Too large	
G. Differential w/Upgraded Ring and Pinion			Usable combinat-ion not found			

Figure 15: Constraint Violation Analysis for Design Alternatives. A black box indicates that the constraint has clearly been violated and a shaded box indicates the possibility that the constraint will be violated. More details are contained in the individual boxes.

According to this analysis, the only usable solution is using the existing gearbox without a clutch. All the other solutions directly violate at least one of the problem constraints. Many of these have to do with the availability of parts. Even the gearbox solution might make it impossible for all hundred batteries to be placed accessibly in the car. Normally at this stage, the designs that did not violate design constraints would be compared on the basis of the stated objectives. However, since the constraint analysis produced a single viable result, this is not necessary. Some comparison is still useful.

5.2. Design Performance Comparison

This section will compare the performance of a number of different gearing designs, even though all but one was rejected in the previous section. These designs will be compared to performance data on the Tesla Roadster, since it is the obvious benchmark for this project. The performance data on the 2005 Lotus Elise will be shown for reference as well. All predicted data was obtained using Frans Ho's performance model.

Gearing	0-60 km/hr Time (s)	0-100 km/hr Time (s)	Top Speed (km/hr)
Original Gearbox 1st gear	2.5	NA	75
Original Gearbox 2nd gear	3.2	7.1	130
Original Gearbox 3rd gear	4.1	7.8	170
Original Gearbox 4th gear	5.3	9.4	200
Differential 5.5:1 gear ratio	4.1	7.8	170
Differential 6.0:1 gear ratio	3.8	7.1	160
Differential 6.5:1 gear ratio	3.5	7.2	145
Tesla Roadster	2.0 (est)	3.6	200
2005 Lotus Elise	2.3	4.9	220

Figure 16: Performance Comparison

The first feature to note from Figure 16 is the versatility that a gearbox gives in terms of acceleration and top speed. A differential is limited to one setup, but a gearbox can give a wide range. The reasons that none of the designs can compete directly with either the 2005 Lotus or the Tesla are worth noting as well. Both the 2005 Lotus and Tesla motors produce roughly twice the power of the UQM motor used in this project. Tesla's motor has roughly the same peak torque, but is able to sustain it up to 5,000 rpm instead of only 3,000 rpm for the UQM motor. Additionally the Tesla motor redlines at 13,000 rpm, as opposed to only 8,000 for the UQM motor (AC Propulsion). Tesla's motor is also not available to the general public. The 2005 Lotus is able to take advantage of multiple gears to overcome the fact that its peak torque is only 80% of the UQM motor (Road Test 2005). The strength of the UQM motor is its ability to produce high torque at low rpms, which is represented in its competitive 0-60 km/hr time in 1st gear.

5.3. Discussion

A comparison of design alternatives concluded that the only feasible solution was to keep the existing gearbox without a clutch, even though it strained the ability of the rest of the mechanical group to fit their components into the vehicle. This design also places more weight on the rear axle than designs involving a differential or the rear-engine transmission. Due to setbacks in the workshop, implementation of any design cannot begin until June 15th. This means that there is time to search for further solutions. During this interim period further investigations will be made it procuring a differential that does not violate any design constraints. One possible solution is shortening an existing differential by removing bearings that support the vehicle drive shaft.

At the present time; however, there is one possible solution and design specifics have continued along this line. The next step is communicating the repercussions of this particular solution with the rest of the mechanical group and insuring that all components can fit. The following sections outline the general layout as well as the specifics of how to mount the motor and gearbox in the engine compartment. These steps fulfill the second and third goals of this project (Figure 2).

5.4. General Layout

The motor and gearbox will be placed as seen in Figure 11. Batteries will be divided up into three cages: one placed in the fuel tank, another on top of the motor and gearbox, and a third underneath the boot. With current designs, this will accommodate ninety-nine of the one-hundred batteries. A cooling pump will be placed to the right of the motor, giving it access to the controller, motor, and existent coolant piping. The motor controller will be placed in the boot. A hole will be cut between the boot and the engine compartment to allow coolant and power to reach the controller. The charger will be placed in the boot as well, while various other electronics can be placed around the motor and gearbox in the engine compartment.

5.5. Motor and Gearbox Mounting

Since the gearbox/motor setup in the Lotus will be similar to what was used in the Getz last year, similar parts will be used to mount them (Tan 2008). The design will require a number of supports that will hold the gearbox and motor in place. It is not possible to incorporate motor mounts in every support, so to prevent excessive stress on the supports without motor mounts; existing motor mounts will be removed. Components necessary to support the motor and gearbox are listed below:

- Adaptor plate to connect structure of motor and gearbox.
- Shafts coupling to connect motor shaft to transmission shaft
- Rear support of gearbox
- Front support of gearbox
- Motor support

Designs for these components will be described briefly below. Stress analysis has yet to be performed and dimensions will be scaled according to results.

Adaptor Plate

An adaptor plate is used to connect the face of the gearbox to the body of the motor. Bolt holes in the adaptor plate need to be placed precisely in order to match the existing holes in the shell of the gearbox. Preciseness will also insure that no weight is carried by the shafts themselves. A cylindrical spacer is then used to reduce the required thickness of the plate, thus saving weight.

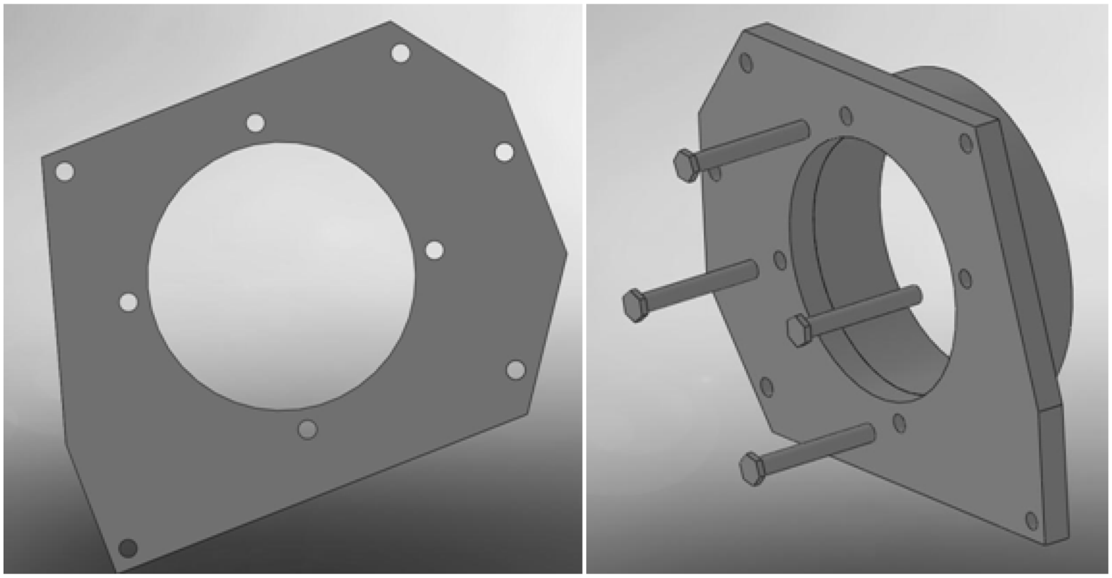

Figure 17: Adaptor Plate Design

The adaptor plate shown on the left is bolted to the motor with bolts running through a cylindrical spacer shown on the right. The motor and adaptor are then bolted to the transmission. The design should securely attach the motor and gearbox without using excessive material.

Spline Coupling

Both the electric motor and the gearbox's driveshaft use a spline coupling to transfer torque. In order to create a sleeve that will match each spline, a specialized wire cutting tool found in the physics workshop must be used. Because the splines are different sizes, two couplings must be produced and bolted together. This design is shown below.

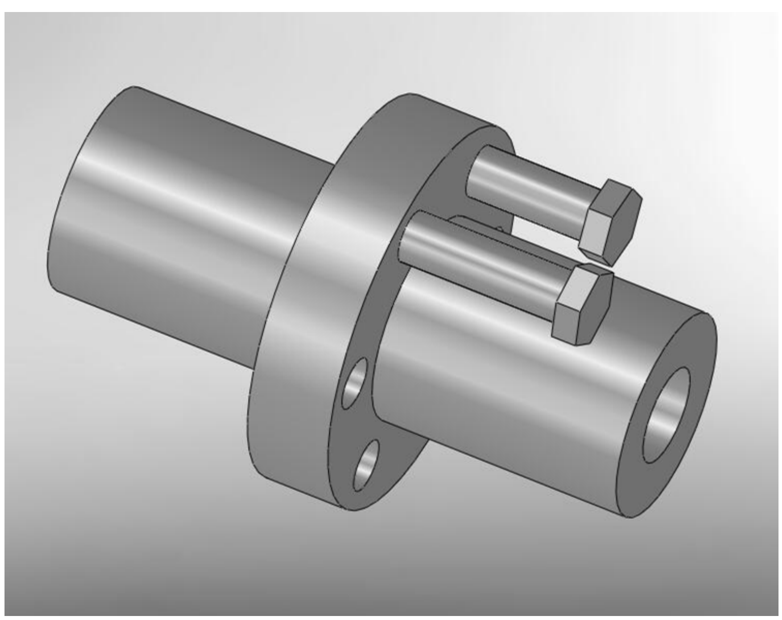

Figure 18: Spline Coupling Component

Rear Support of Gearbox

The original rear gearbox support will be used. However, the rubber motor mount will be removed in order to decrease stress on undamped connections.

Front Support of Gearbox

After working with Christian Tietzel, who is designing the battery cages for the Lotus, the following design has been decided upon because it will support the front of the transmission as well as provide a strong platform for the battery cage which will rest above the gearbox and motor. Steel support bars will be added to the front and rear of the engine compartment. A support bar will run between these which will support the front of the gearbox through the adaptor plate directly into the gearbox shell. This way the gearbox is securely supported from both ends.

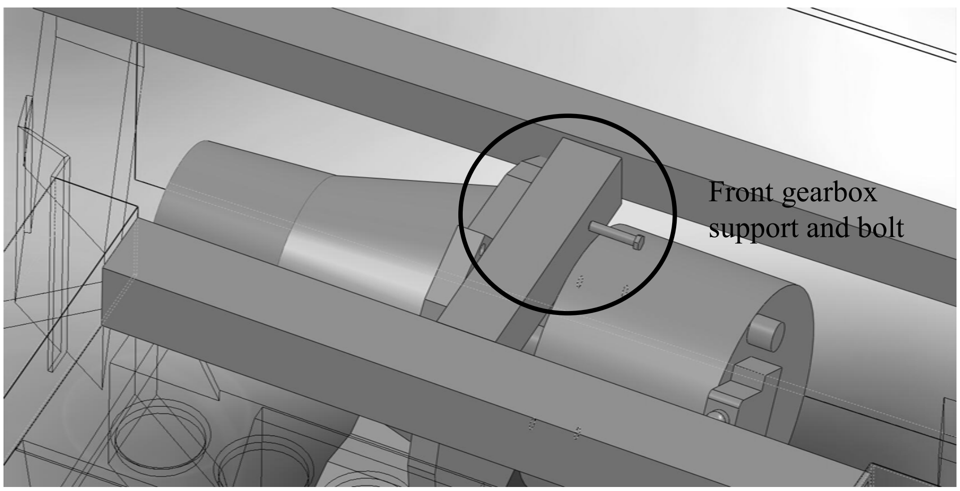

Figure 19: Front Gearbox Support and Frame

Motor Support

The motor will be supported by the adaptor plate, previously mentioned, as well as a support bar running underneath it. The motor will simply rest on this bar, which will remove the load from the adaptor plate.

6. Conclusion

The REV Project's goal during the current academic year is to produce a street-legal electrically driven Lotus Elise. The part of that undertaking described here is the design of the drive system mechanics. This design project began with three goals. The first was to select from a number of design alternatives, an optimal design for the drivetrain of the vehicle. Only one usable solution was produced as all other design alternatives violated a fundamental restriction placed on the design. The chosen design was to leave the original gearbox in the vehicle. This design provides flexibility to acceleration times and top speed, but leaves little leftover space in the engine compartment for other group members to use. The second goal was to ensure that all required components could fit in the vehicle given the chosen design. This was accomplished, although currently one of one-hundred batteries has been left out, which has been deemed acceptable. The last goal was to design a system to mount and connect the gearbox and motor in the engine bay. The basic designs for this task have been completed as well.

The results of this project should produce an electric vehicle that is fun to drive and draws the attention and interest of the general public. A goal of the REV project is to promote electric cars though education and demonstration in the community and an electric Lotus Elise should be an excellent way to accomplish this.

7. Further Work

Further work is obviously needed to complete this project. During the current delay in the electrical engineering workshop, further research will be conducted into available differentials and if a differential could be shortened by removing nonessential parts. If a suitable alternative is found, further work would be required to resign the overall component layout. The mounting design would need to be redone as well. Once designs are finalized, stress analysis can be done to determine specific dimensions of the parts.

When work resumes in the workshop, production will begin on the adapters and other supports for the motor and gearbox/differential. Once this is done the drivetrain can be installed and tested. This will allow the battery cages and other components to be installed as well. Once the mechanical group has finished installing its components, the electrical and instrumentation groups can complete the vehicle.

References

"AC Propulsion EV Drive System Specifications". AC PROPULSION INC. <www.acpropulsion.com>.

Chapman, G., (2007), "Renault Fuego", The Independent: Motoring.

Filipponio, F., (2009), "Detroit 2009: BYD e6 - world's first production dual-mode plug-in hybrid crossover", Autoblog, Jan 12th 2009.

Handy, J., (1937), "Around the Corner" Chevrolet Division, General Motors Corporation, <http://www.archive.org/details/Aroundth1937>.

Mathew, R (2008), "The REV Project: Electric Vehicle Design Concepts and Project Management", School of Electrical, Electronic and Computer Engineering at the University of Western Australia.

Paine, C. 2006, Who Killed the Electric Car?, [Documentary], Sony Pictures Home Entertainment.

"PG1 Transmission," Powertrainltd. <www.powertrainltd.com>.

"PowerPhase® 75 Traction System", UQM Technologies, <www.uqm.com>.

"Road Test: 2005 Lotus Elise". <www.lotuscars.com>

Tan, D.Z. (2008), "Design and Construction of Motor Mounts for Renewable Energy Vehicle", School of Mechanical Engineer at the University of Western Australia.

"Terios 7 seater", (2008), Daihatsu Motor CO., Ltd., <www.daihatsu.com>.

"Toyota 7.5", <www.differentials.com>.

Tate, E.D., Harpster, M.O., & Savagian, P.J. (2008), "The Electrification of the Automobile: From Conventional Hybrid, to Plug-in Hybrids, to Extended-Range Electric Vehicles", General Motors Coporation.

Appendix I: UQM Technologies, Inc. PowerPhase® 75 Traction System
®

Figure 20: PowerPhase® 75 Traction System

This appendix serves to provide relevant details regarding the electric motor used in this project.

Parameter	Value
Peak Torque	240 Nm
Peak Power	75 kW
Full Power VDC input	250 – 400 V
Max Input Current	400 A
Mass	41kg
Max Motor Speed	8000 rpm

Figure 21: Electric Motor Parameters

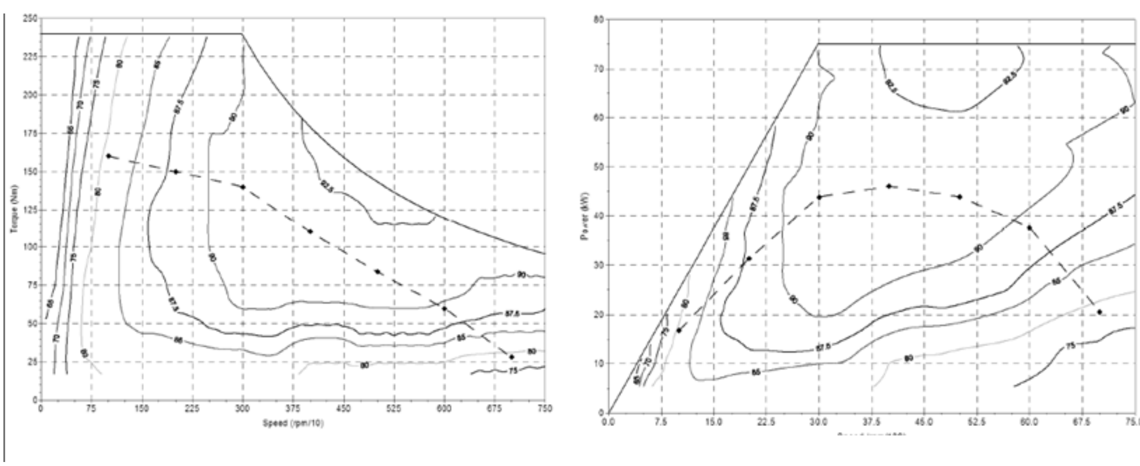

Figure 22: Torque and Power Curve for Electric Motor

All data and images are taken from public sources (PowerPhase® 75 Traction System).

Appendix II: PowertrainLTD PG1 Gearbox

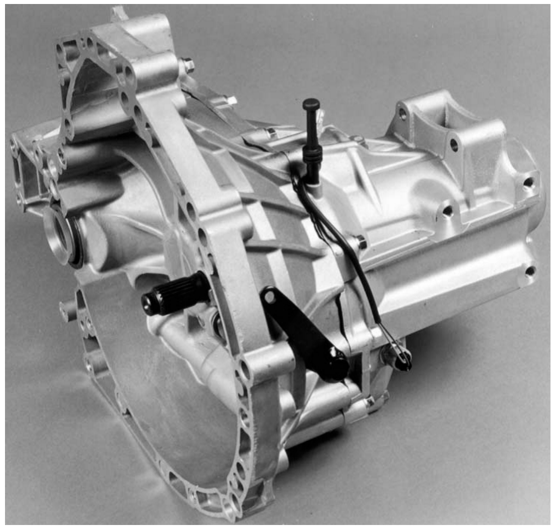

Figure 23:PowertrainLTD PG1 Gearbox

This appendix will provide further details about the original gearbox in the Lotus Elise.

Gear	Ratio
1st	2.92
2nd	1.75
3rd	1.31
4th	1.03
5th	0.85
Rev.	3.00
Final Ratio	4.20

Figure 24: Gearbox Gear Ratios

Parameter	Value
Mass	36 kg
Max Torque	240 Nm

Figure 25: Gearbox Data

All data and images are taken from public sources (PG1 Transmission).