

## **Regenerative Braking on the Lotus Renewable Energy Vehicle**



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## **1. Project Summary**

The fossil fuels used in transportation have a negative effect on the environment and are also in declining supply. Alternative technologies need to be introduced in order to reduce our dependence on oil and to allow us to live a sustainable lifestyle. Electric vehicles are a viable alternative to internal combustion engine (ICE) vehicles. However, they are somewhat limited in their driving range. Regenerative braking allows an electric vehicle to travel farther per charge by recapturing energy lost during braking. The goal of this project was to implement an effective regenerative braking system on the Lotus Elise Renewable Energy Vehicle.

Research was carried out to investigate the best possible way to implement such a system. From this research, a parallel regenerative braking system was chosen and a theoretical analysis was conducted to ensure that the vehicle remained safe with the new system. The analysis showed that the regenerative braking system would enhance the braking performance of the REV Elise, while making it safer at the same time.

A custom braking and accelerating control system was designed, manufactured and installed. The acceleration system worked effectively and produced the correct acceleration input to the electric motor controller. There was not enough time to fine tune the braking system to produce the desired braking input. However, the braking system design was effective with no major design flaws and it will produce the correct braking input signals once it has been adjusted. The objectives of the project were successfully completed.

**Table of Contents**

1. Project Summary .....	2
2. Introduction .....	5
2.1 Overview.....	5
2.2 Braking Theory.....	5
2.2.1 Braking Force .....	5
2.2.2 Braking Distribution.....	6
2.2.3 Vehicle Stability .....	9
2.2.4 Energy Consumption during Braking.....	10
2.3 Regenerative Braking Systems .....	12
2.3.1 Series Braking with Optimal Feel .....	13
2.3.2 Series Braking with Optimal Energy Recovery .....	13
2.3.3 Parallel Braking.....	14
3. Design and Implementation.....	14
3.1 Choosing the Regenerative Braking System .....	14
3.1.1 Sophisticated Series Braking System.....	14
3.1.2 Simple Series System.....	15
3.1.3 Parallel Braking System with Creep Control .....	15
3.1.4 The Proposed System.....	16
3.2 Theoretical Analysis of Braking System .....	17
3.2.1 Analysis .....	17
3.2.2 Analysis Conclusions .....	23
3.3 Design of the regenerative Braking System .....	23
3.3.1 Regenerative Braking Control.....	23
3.3.2 Design Considerations.....	24
3.3.3 Design of the braking and acceleration systems .....	25

4. Results and Discussion ..... 27

5. Conclusions and Future Work ..... 31

6. References ..... 32

Appendix A – Graph Data ..... 33

Appendix B – CAD Drawings for Custom Parts ..... 36

## **2. Introduction**

### 2.1 Overview

The burning of fossil fuels in transportation has a significantly adverse effect on the environment and contributes to global warming. Additionally, world oil supply is limited and is expected to run out by 2045 (Shuster 2008). In order to free the world from its dependence on fossil fuels and to allow mankind to live in a sustainable manner, alternative transportation technologies need to be developed. The REV project is developing electrically powered Renewable Energy Vehicles to showcase the viability of alternative technologies. One of the problems with electric vehicles is that they have a lower range per charge than conventional Internal Combustion Engine (ICE) vehicles have per tank. To increase the range, electric vehicles are able to take advantage of regenerative braking, whereby the motor is run as generator during braking to convert kinetic energy into electrical energy to charge the battery. The effectiveness of a regenerative braking system depends on the driving conditions as well as the way the vehicle is driven. However, studies have shown that a regenerative braking system can increase a vehicle's range by 10-15% (Dhameja, 2001). Conveniently, regenerative braking is most effective in the stop-and-go conditions of urban driving, which most cars are subjected to on a daily basis (Ehsani, 2004). Engineers of the all-electric Tesla Roadster found that regenerative braking improved their car's efficiency by 40 % in city driving conditions (Simpson, 2007). Thus, regenerative braking can significantly improve the fuel economy of electric vehicles and can help make electric vehicles a viable replacement for ICE vehicles.

The objective of this project is to research, design and implement the most effective regenerative system on the Lotus Renewable Energy Vehicle. This implementation will have to take into account the budget of the REV project, the time frame of the project and the constraints of the given vehicle design.

### 2.2 Braking Theory

#### *2.2.1 Braking Force*

When a braking torque, such as the torque produced by conventional friction brakes, is applied to a wheel, it produces a braking force in the tire-ground contact area that acts to slow the car. The braking force will increase with braking torque until it reaches the maximum force that the tire-ground adhesion can support. The maximum braking force depends on the

adhesive coefficient of the tire-ground contact area,  $\mu_b$ , and on the weight of the car,  $W$ .

Equation 2.1 gives the expression for maximum braking force.

$$F_{bmax} = \mu_b W \quad (2.1)$$

Beyond this point, it is possible to increase the braking torque but not the braking force. The slip,  $s$ , of a tire compares the vehicle's speed to the speed of the tire. In braking, slip can be defined as:

$$s = \left(1 - \frac{r\omega}{V}\right) \times 100\% \quad (2.2)$$

where  $V$  is the horizontal speed of the tire centre,  $\omega$  is the angular speed of the tire and  $r$  is the rolling radius of the tire. Braking force increases with the applied torque to a maximum at 15-20% slip and then declines as slip approaches 100% (Ehsani et al, 2009). 100% slip is the point where the wheel is locked and the car skids. The braking force that a car can produce largely depends on the surface it is travelling on. For example, a car travelling on ice will take longer to come to a stop than a car on a tar road.

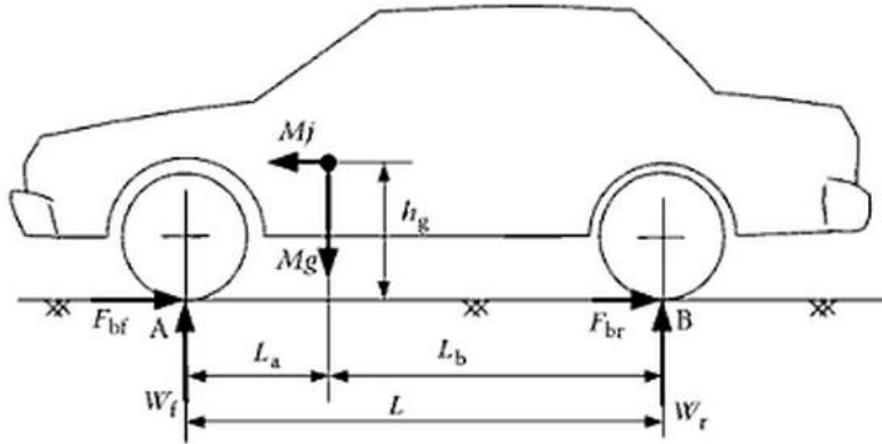
### 2.2.2 Braking Distribution

The total braking force on a car is the sum of the braking forces on the front and rear wheels.

Using Newton's second law of motion, the deceleration can be expressed as

$$j = \frac{F_{bf} + F_{br}}{M_v} \quad (2.3)$$

where  $j$  is the deceleration,  $F_{bf}$  is the braking force on the front wheels,  $F_{br}$  is the braking force on the rear wheels and  $M_v$  is the mass of the vehicle. Figure 1.1 shows the forces acting on a car during braking. The forces due to rolling resistance and aerodynamic drag are small in comparison to the braking forces and can be left out.



**Figure 2.1:** Forces acting on a car during braking. [Image from: Ehsani et al, 2009]

During braking, load is transferred from the rear axle to the front axle. By considering the moment balance about points A and B, the weight over the front and rear axles can be expressed by

$$W_f = \frac{M_v g}{L} \left( L_b + \frac{h_g j}{g} \right) \quad (2.4)$$

$$W_r = \frac{M_v g}{L} \left( L_a - \frac{h_g j}{g} \right) \quad (2.5)$$

where  $W_f$  and  $W_r$  are the normal loads on the front and rear axles, respectively, and  $g$  is the acceleration due to gravity. Because the maximum braking force produced by each set of tires is proportional to the normal load on the tires, the braking force (and braking torque) should also be proportional to the load on the tires. In this way, both the front and rear tires will produce their maximum braking force at the same time and will be able to stop a car in the shortest distance possible. If one set of tires reached its maximum braking force before the other set, then the total braking force would be less than the maximum total braking force and the car would travel a longer distance before it came to a stop. The ratio of braking force is equal to the ratio of normal load. This can be expressed as

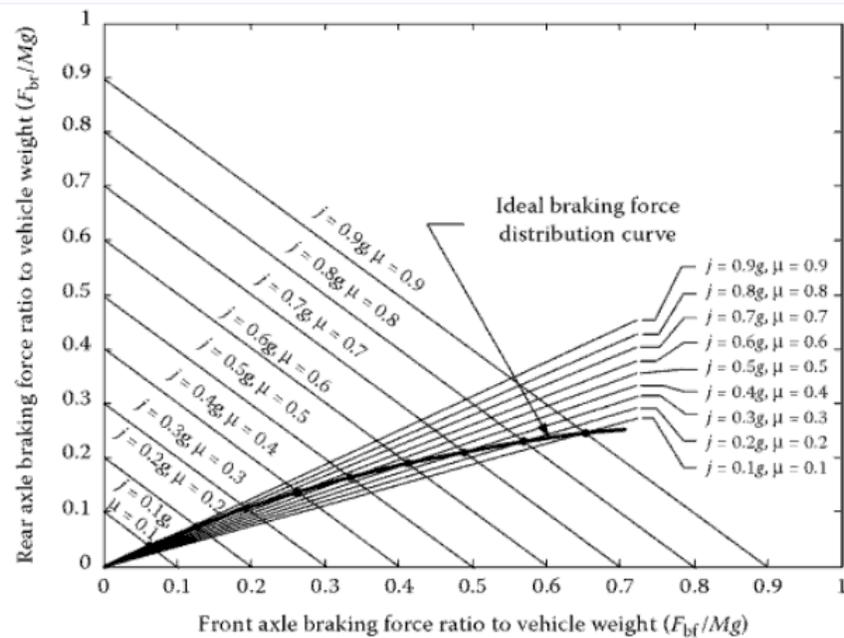
$$\frac{F_{bf}}{F_{br}} = \frac{W_f}{W_r} = \frac{L_b + h_g j / g}{L_a - h_g j / g} \quad (2.6)$$

where  $F_{bf}$  and  $F_{br}$  are the braking forces at the front and rear, respectively. By substituting equation 2.3 into 2.6, it is possible to solve for the force of braking at the front and rear. These are expressed by

$$F_{bf} = \frac{jM_v}{L} \left( L_b + \frac{h_g j}{g} \right) \quad (2.7)$$

$$F_{br} = \frac{jM_v}{L} \left( L_a - \frac{h_g j}{g} \right) \quad (2.8)$$

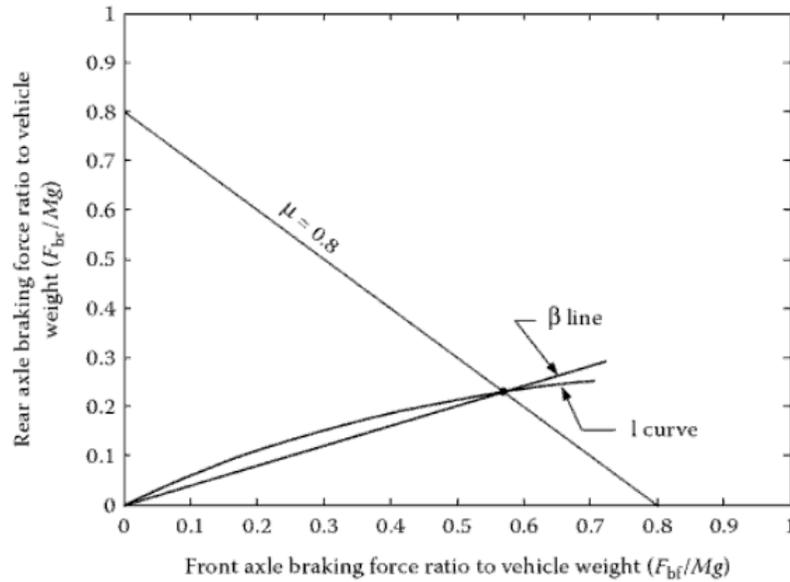
Using the above equations, it is possible to plot a curve of the ideal braking forces. This can be expressed in terms of dimensionless numbers and is shown in Figure 2.2.



**Figure 2.2:** The ideal braking forces on the front and rear axles.

[Image from: Ehsani et al, 2009]

As can be seen from Figure 2.2, the ideal braking distribution forms a nonlinear curve. In practice, the actual braking distribution is designed to follow a fixed ratio between front and rear. This is a result of the properties of the hydraulic braking systems that are used in most vehicles. In a purely mechanical braking system, with no electronic assistance (as in the case of a Lotus Elise), the front and rear braking distribution can only be a fixed ratio as determined by the surface area of the pistons within the brake calipers. As the brake pedal is pushed, the braking force will increase, but always in the same front/rear ratio since the surface area of the pistons is fixed. As such, the actual braking distribution will be a straight line that best fits the ideal distribution. This is illustrated in Figure 2.3 where the ideal distribution is denoted as the  $I$  curve and the actual distribution as the  $\beta$  curve.



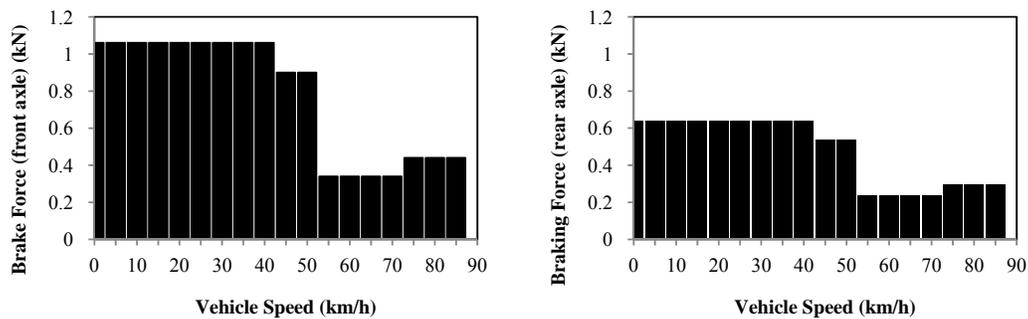
**Figure 2.3:** A plot of the actual braking distribution ( $\beta$  curve) and the ideal braking distribution (I curve). [Image from: Ehsani et al, 2009]

### 2.2.3 Vehicle Stability

As can be seen from Figure 2.3, the actual curve will only intercept the ideal curve at one point, and it is at this point only that the front and rear tires will lock up at the same time. This point represents a specific road adhesive coefficient,  $\mu$ . For all road adhesive coefficients less than  $\mu$ , the front wheels will lock up before the rear wheels, whereas for road adhesive coefficients greater than  $\mu$ , the rear wheels will lock up first. This has important implications for the vehicle stability. If the rear wheels lock, the vehicle will lose directional stability as the rear wheels lose the ability to resist lateral forces (Ehsani et al, 2009). If a slight lateral force is initiated, such as that from wind or a centrifugal force, the car will spin out of control. In contrast, if the front wheels lock, the vehicle will lose directional control, but not directional stability (Ehsani et al, 2009). This means that the driver will lose the ability to steer the vehicle left or right, but the vehicle will remain on a straight path. Loss of directional control may be rectified by releasing the brakes slightly. However, once the rear wheels are locked and the vehicle has spun out to a certain level, control of the vehicle cannot be regained, even by releasing the brakes fully. It is therefore very important that the rear wheels do not lock up first.

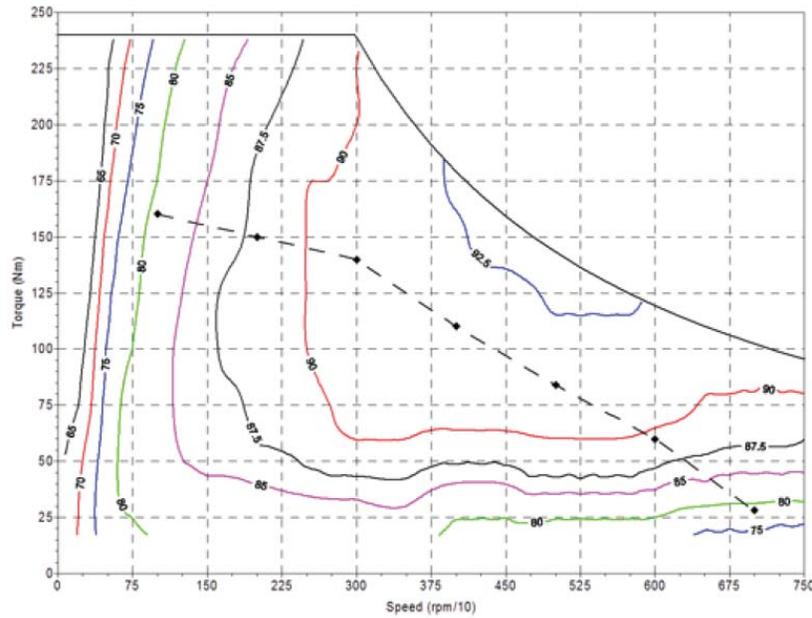
### 2.2.4 Energy Consumption during Braking

A significant amount of energy is consumed during braking. As an example, braking a 1500kg car from 100-0 km/h consumes about 0.16 kWh of energy in a few tens of meters. If the car were allowed to coast to a stop, being slowed only by aerodynamic drag and rolling resistance, it would travel about 2km. When vehicles are driven in urban areas, a large amount of energy is consumed by the stop-and-go pattern which consists almost entirely of acceleration followed by braking induced deceleration (Ehsani et al, 2009). An FTP-75 (Federal Test Procedure) driving cycle is a standard test used to emulate the conditions of everyday, urban driving. Figure 1.4 below shows the braking forces on the front and rear wheels of a passenger car during a FTP-75 driving cycle. Referring to Equation 2.7 and 2.8, this car has parameters of  $M_v=1500\text{kg}$ ,  $L=2.7\text{m}$ ,  $L_a=0.4L$ ,  $L_b=0.6L$  and  $h_g=0.55\text{m}$ .



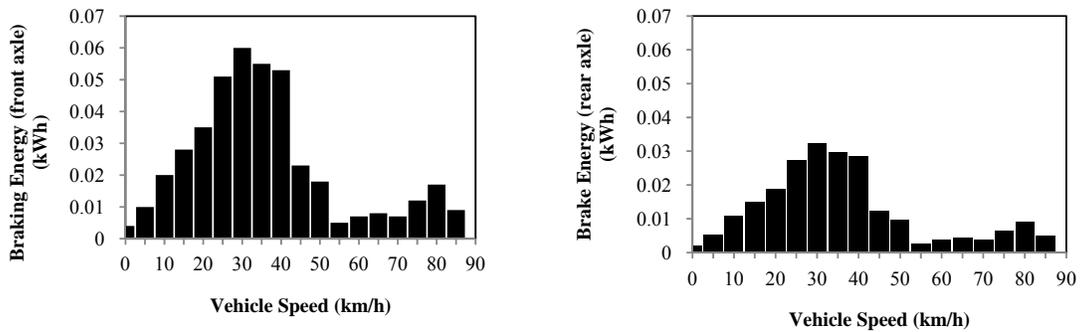
**Figure 2.4:** The braking forces on the front and rear wheels vs. vehicle speed during an FTP-75 drive cycle. [Image reproduced from: Ehsani et al, 2009].

From Figure 2.4 it can be seen that the required braking force is at a maximum in the region from 0-40 km/h. The required braking force is almost constant in the region below 50km/h and then decreases for speeds above 40 km/h. This characteristic matches the torque curve of an electric motor, which has a constant and maximum torque below base speed and a hyperbolically decreasing maximum torque above base speed. Figure 2.5 shows the torque curve of the UQM PowerPhase 75 motor used in the REV Elise.



**Figure 2.5:** The torque vs. engine speed for the UMQ PowerPhase 75 electric motor. [Image from: UQM Technologies, 2009].

The fact that the torque curve matches the braking force curve is convenient because it means that the maximum torque will be available at the speeds at which it is most needed. This will be further discussed in Section 3. Figure 2.6 shows the energy consumed by braking for the 1500kg car being tested on the FTP-75 driving cycle.



**Figure 2.6:** The braking energy consumed by the front and rear wheels vs. vehicle speed during an FTP-75 drive cycle. [Image reproduced from: Ehsani et al, 2009].

From Figure 2.6 it can be concluded that most energy is consumed in the range of 10-50km/h. Furthermore, the front brakes on this car consume about 65% of total braking energy. This means that regenerative braking is more effective on the front wheels of the car. The REV

Elise is a rear-engined car and as a consequence, the regenerative braking will have to be implemented at the rear wheels. This is not an ideal situation since there is more available energy at the front wheels. However, the weight distribution of the Lotus is biased towards the rear, as opposed to the car above which is biased towards the front. This means that the energy available for recovery at the rear wheels will be greater than 35% for total braking energy due to the extra load on the rear wheels. However, the front wheels will still consume the most braking energy due to the moment balance given by Equations 2.7 and 2.7.

### 2.3 Regenerative Braking Systems

The fundamental principles of regenerative braking are based on the laws of electromagnetism. When a conductor is placed in a changing magnetic field, a voltage will be induced across the conductor. This voltage is known as the electromotive force (emf). In accordance with Lenz's law, the emf induced in an electric circuit always acts in such a direction that the current it drives around the circuit opposes the change in magnetic flux which produced the emf. In the context of generators, the emf is known as back emf and it will produce an electromagnetic force in accordance with the Lorentz force law which applies a negative torque on the rotor and causes the rotor to decelerate. If there is a circuit connected to the terminals of the emf source, current will be driven through the circuit. In an Electric Vehicle, a regenerative braking system works by running the electric motor as a generator. The kinetic energy or mass potential energy provides the driving force for the generator. The battery circuit is connected to the terminals of the motor and current is driven into the batteries. At the same time, the motor slows down due to the negative torque acting on it and this produces the braking effect.

In the case of emergency or hard braking, large amounts of energy are dissipated in a short amount of time (Ehsani et al 2009). Most electric engines are not rated to handle this power and as a consequence, a conventional friction braking system is required in addition to regenerative braking to provide the extra force (Husain 2003). Furthermore, there are situations where the regenerative braking may be limited, for example, if the batteries are fully charged and can accept no more current. In this case, the frictional braking system is necessary to stop the vehicle. The frictional braking system also adds a backup system in the off chance that there is a failure with the regenerative system.

Braking is one of the most important factors affecting the safety of a vehicle. As such, the regenerative braking system needs to be implemented with the friction braking system to maximize the safety of the vehicle. This requires that, firstly, in an emergency braking situation, the braking system is able to stop the vehicle in the shortest possible distance. This means that the system must be able to supply sufficient braking torque on all four wheels. Secondly, the vehicle must maintain directional stability during braking. This means that the braking force should be distributed in proportion to the normal loads on the tires.

According to Ehsani et al (2009), there are three strategies for regenerative braking control: series braking with optimal feel, series braking with optimal energy recovery and parallel braking.

### *2.3.1 Series Braking with Optimal Feel*

Series Braking with optimal feel uses a braking controller to control braking forces on the front and rear wheels. When the commanded deceleration (represented by the position of the brake pedal) is low, only regenerative braking is used. For more aggressive deceleration, the controller adjusts brake force such that the distribution between front and rear follows an optimal curve. The regenerative braking will be used up to its maximum torque and friction braking will be used to provide the rest of the necessary force. The maximum torque of the motor is related to its speed. At lower speeds, maximum torque is constant but at higher speeds, it decreases hyperbolically with speed. Therefore, the applied frictional brake force at a given deceleration will vary with speed. As a result, active control of the friction brakes is necessary. This adds a large degree of complexity to the system. It requires that there is an electrical system in place to actuate both the friction and regenerative braking systems simultaneously. Unlike conventional friction braking systems, based purely on hydraulic pressure developed directly by the driver, there is no direct link between the driver and the braking systems. The driver determines the total required braking force as a function of pedal position, but the electronic controller and braking servos are responsible for distributing this total force in an optimum way between front and rear wheels, and between regenerative and frictional braking systems.

### *2.3.2 Series Braking with Optimal Energy Recovery*

When the vehicle is decelerated at a ratio of deceleration relative to gravity that is less than the adhesive coefficient of the road, the forces on the front and rear wheels can be varied

within a certain range. Series braking with optimal energy recovery uses the same control mechanisms as the Optimal Feel system but it biases the braking towards the wheels connected to the motor in order to recover as much energy as possible. A downside of this is that the braking distribution between front and rear may not be optimal.

### *2.3.3 Parallel Braking*

Parallel braking is a much simpler design as there is no need for electronic control of the frictional brake system. The frictional brake system has a fixed distribution between front and rear. Both the frictional and the regenerative system apply braking torque in response to hydraulic pressure in the master cylinder (or in response to brake pedal position). When the required deceleration is low, only the regenerative braking is used and this emulates the engine braking effect in ICE vehicles. The parallel method has a much simpler construction and control system, but the amount of energy recovered and the feel of the brakes is compromised.

## **3. Design and Implementation**

### 3.1 Choosing the Regenerative Braking System

There were a number of possible implementation ideas for the regenerative system, as well as a number of limitations on these systems. The most important limitation is that it is desirable not to modify the existing friction braking system in anyway. The frictional braking system is tried and tested and, more importantly, acknowledged as a safe braking system by the authority responsible for licensing vehicles. Not modifying the existing system ensures that there is a fail proof backup system to compliment the regenerative braking system which is in its first iteration of design. Furthermore, since the REV Elise is ultimately meant to be a licensed, road-legal car, having a factory installed braking system will make a strong case for the safety of the car. A number of possible implementations are discussed below.

#### *3.1.1 Sophisticated Series Braking System*

A well designed series braking system would provide the best efficiency and driver feel. However, this would require a complete modification of the friction braking system. A smart controller would receive a braking signal based on the braking pedal position. It would then translate this signal into the necessary braking force and would distribute this force between the front and rear wheels and between the regenerative and frictional systems. The distributing

of force would be based upon real-time evaluation of engine speed and input brake demand, as well as many other physical parameters of the vehicle. This system would take direct control away from the driver. Should a servo fail or a connection become loose, the brakes would be partially or completely disabled, making the car unsafe. According to Ehsani et al (2009), a fail-safe, sophisticated system such as this is still under research and development.

### *3.1.2 Simple Series System*

Another idea was to implement a simple series system that did not involve the complexities of a smart controller or servos. This could be accomplished by modifying the range of the brake pedal. By increasing the range of the brake pedal it would be possible to bring in regenerative braking up to its maximum torque and then bring in the frictional braking. The brake pedal could be modified using a telescopic mechanism that would only allow the pedal to make contact with the hydraulic master cylinder once the regenerative braking was being used at its maximum. There are a few problems with this system. Firstly, it would mean making large modifications to the existing braking system which is undesirable. It would also upset the braking balance because the regenerative braking torque would cause a strong bias at the rear and this may cause stability issues. Since the torque range of the regenerative braking depends on engine speed, the brakes would feel very different at different engine speeds. Below base speed the driver would feel a constant torque range. At speeds above base speed, the torque range decreases and so the driver would have to push the pedal in further to get the same torque. This produces a confusing and potentially dangerous scenario.

### *3.1.3 Parallel Braking System with Creep Control*

A parallel braking system will not require any modification to the frictional braking system. However, the energy recovered from the system will be less than the previous two options. In the parallel system, a braking torque demand will be developed based on the position of the brake pedal. This signal will be sent to the motor controller which will produce a braking torque. The regenerative torque will be directly parallel to the frictional torque i.e. the regenerative torque will reach its maximum value at the same time as the torque caused by frictional braking. The braking system will feel slightly different depending on the engine speed but it should not be as severe as the simple series system, since the frictional braking system in parallel always feels the same. Furthermore, in an urban driving cycle, the required braking torque is highest in the 0-50km/h range. The braking torque range of the electric motor is constant below base speed as shown by Figure 2.5. The REV Elise will be using the 2<sup>nd</sup> and

4<sup>th</sup> gears of the existing gear box. The engine's base speed of 3000 rpm translates to 50km/h road speed in 2<sup>nd</sup> gear and 80 km/h in 4<sup>th</sup>. It is also worth mentioning that the speed limits within Western Australia are 60 km/h for major metropolitan areas while suburban streets are limited to 50 km/h (westernaustralia.com, 2009). This means that drivers in metropolitan areas will experience a constant braking feel, independent of engine speed provided they are travelling within the speed limits. Additionally, the driver will have the maximum regenerative torque available during this speed range, which is convenient because this is the speed range in which most energy can be recovered (Ehsani et al, 2009). For higher speeds, there will be less regenerative braking torque available. However, as demonstrated by Figure 2.4, the desired braking force at higher speeds is generally less than that at lower speeds. In this case, the decrease in braking torque at higher speeds may actually add to the driver's braking experience, and not detract from it.

A small amount of regenerative braking will also be applied when there is neither a braking nor an acceleration demand. This will be implemented using the built in Creep Control of the motor controller and it will simulate the engine braking effect of ICE vehicles. The purpose of this is to allow the driver to make use of full regenerative braking without losing any energy to friction braking. Ultimately, a large part of the range of an electric car depends on how it is driven. The range will be greatly extended if the driver avoids hard acceleration and braking. If the driver allows a longer distance for stopping, then the car can be decelerated using only the regenerative braking.

#### *3.1.4 The Proposed System*

Both of the series systems involve modification of the frictional braking system. Because of this and the other disadvantages mentioned above, neither of the series systems will be implemented. Thus the system to be implemented is the parallel system with creep control. This system is the best fit for the current REV project and is the only way to implement regenerative braking without modifying the frictional brakes. In addition to the functionality mentioned above, it must also be possible to turn the regenerative system on and off. In the off chance that the final implementation does not work well, it can easily be disabled. Additionally, there may be situations where regenerative braking is not effective or necessary. An example is if the car were raced around a track. The parallel system is not effective at very high vehicle deceleration and may upset the braking balance. Since the frictional braking

system is always available, it will not hurt to have the option to switch the regenerative braking off.

### 3.2 Theoretical Analysis of Braking System

#### *3.2.1 Analysis*

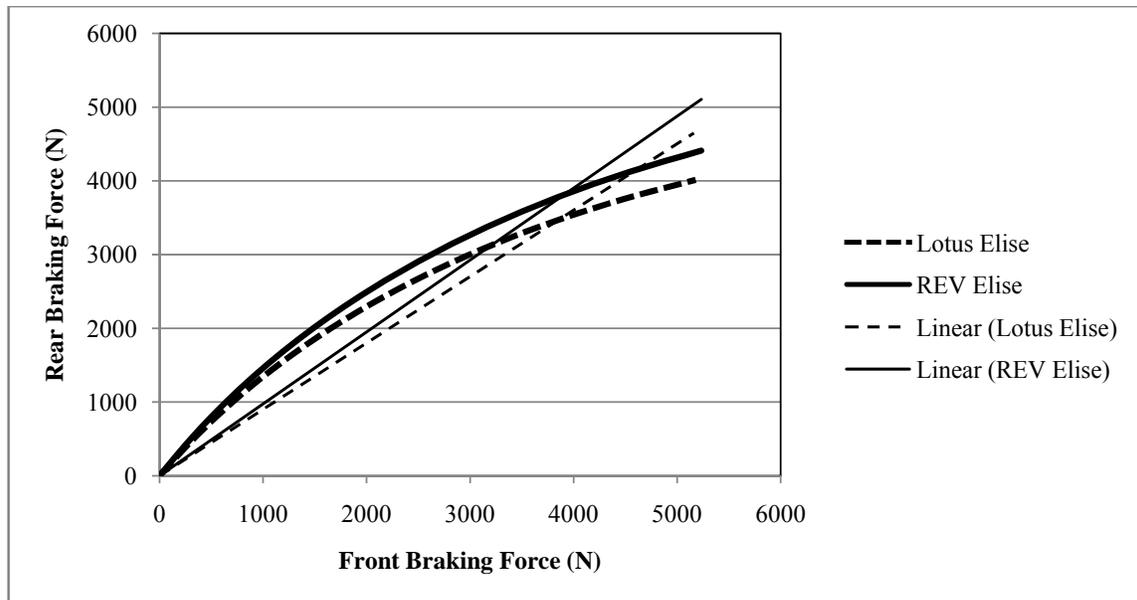
Before proceeding with the final design, an analysis in terms of the braking theory was conducted to determine if the additional regenerative braking torque would significantly upset the braking balance. It should be noted in this section that, even though every effort was made to obtain accurate input data, certain information and parameters were not available. As a result it was necessary to make a few assumptions in order to proceed with the analysis. As such, the results will not be entirely accurate but they should provide a good approximation of the behaviour of the new braking system.

The ideal braking curve describes the optimum ratio of maximum front and rear braking force so that the car will achieve the minimum stopping distance at a given road adhesive coefficient. This curve can be determined by plotting Equation 2.8 against 2.7. Table 3.1 summarises the parameters used in these equations for both the REV Elise and the standard Lotus Elise. Note that the REV Elise is 50 kg heavier due to the addition of batteries. This analysis will evaluate the case of the car containing two 80kg passengers. The height of the centre of gravity was not able to be determined and needs to be assumed. The car tested on the FTP-75 was a typical 1500kg, front-engined car with  $h_g=0.55\text{m}$ . It is not known what car was actually used, however, the Toyota Camry is a typical, front-engined car that weighs 1500kg and has a roof height of 1.470m (Toyota.com.au, 2009). If we take the ratio of  $h_g$  to roof height for the Camry, and apply the same ratio to the lotus it is possible to estimate the height of the centre of gravity based on the total height of the car. The horizontal lengths from the centre of gravity to the axles is determined using the weight distribution on the front and rear axles. All known dimensions for the Lotus are taken from the Lotus Elise Service Notes Manual.

	REV Elise	Lotus Elise
Length (L)	2.3 m	2.3 m
Percentage weight distribution (front/rear)	36/64	38/62
Length to centre of gravity from front axle ( $L_a$ )	1.472 m	1.426 m
Length to centre of gravity from rear axle ( $L_b$ )	0.828 m	0.874 m
Height of centre of gravity	0.42 m	0.42 m
Vehicle Mass with two passengers ( $M_v$ )	984 kg	934 kg

**Table 3.1:** Braking force parameters for the REV Elise and the standard Lotus Elise.

The last variable in calculating the braking force is the deceleration ( $j$ ). In order to plot the braking forces, it is necessary to know the range of deceleration that the vehicles may be subjected to. It was not possible to find deceleration tests on the exact version of the Lotus Elise that is being converted into the REV Elise. However, according to a test conducted by Modified Magazine (2000), a performance enhanced Lotus Elise pulled 1.02 g in a 60-0 mph braking test. According to Sands Mechanical Museum (2009), a series 1 Lotus pulled 0.83 g doing the same test. Note that the units of deceleration being use are g, meaning g-force. This is just the deceleration in  $m/s^2$  divided by gravity ( $9.81 m/s^2$ ). The g-force provides a dimensionless description of the deceleration relative to gravity at the earth's surface. Since the Lotus being used in the REV project is a series 2 Lotus Elise, it is expected that it would perform better than the Series 1 model. However, it is unlikely to perform better than the performance enhanced Lotus Elise. It is therefore a safe assumption to pick a deceleration range from 0-1 g. Figure 3.1 shows the ideal braking force curve calculated with Equations 2.7 and 2.8. Note that aerodynamic drag and rolling resistance are left out since they are small relative to the braking forces. The data used to produce this graph is listed in Appendix A.



**Figure 3.1:** The ideal braking force distribution between the front and rear wheels for deceleration between 0 and 1 g. Linear lines of best fit are also shown.

The trend in Figure 3.1 has a similar shape to that in Figure 2.2. However, there is more emphasis on the rear braking force than that of Figure 2.2 due to the large amount of weight over the rear axle. As mentioned previously, the Lotus Elise has a fixed ratio between front and rear braking force. Information was not available from the manufacturer about this ratio, but it can be determined using the gradient of the linear line of best fit. By using this method, the braking distribution between front and rear for the Lotus Elise is 53% and 47%, respectively. For the REV Elise it is approximately 51% front and 49% rear. The regenerative braking system has to be implemented at the rear wheels since this is where the motor is connected. In section 2.2 it was mentioned that about 35% of total braking energy for a common, front-engined car is dissipated at the rear wheels. For the Elise, about 50% of braking energy will be dissipated at the rear wheels. This means that the regenerative system placed on the rear wheels of the Lotus has more energy available to it than it would have on a front-engined car. The near 50/50 braking distribution means that implementing the regenerative braking at the rear wheels should be as effective as implementing it at the front wheels.

It can be seen from Figure 3.1 that the REV Elise requires more braking force than the Lotus Elise. This is due to the additional weight. To further investigate the braking balance, it is necessary to know how the additional braking force must be distributed between front and

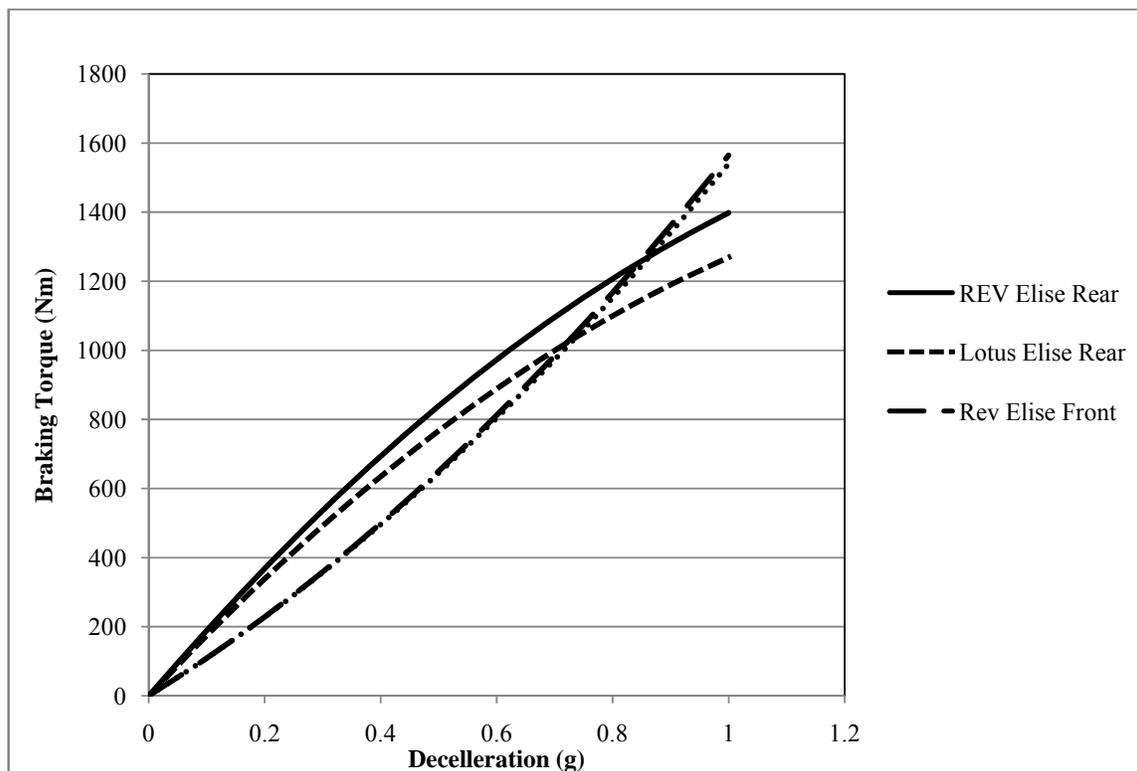
rear. Since the motor controller produces a torque output, it is better to work with the braking torque at the wheels instead of the force. Torque is given by

$$\tau = r \times F \quad (3.1)$$

where  $\tau$  is the torque,  $r$  is the radius and  $F$  is the force. Since the force at the tire-ground contact area is always perpendicular to the radius, torque can be simplified as

$$\tau = rF \quad (3.2)$$

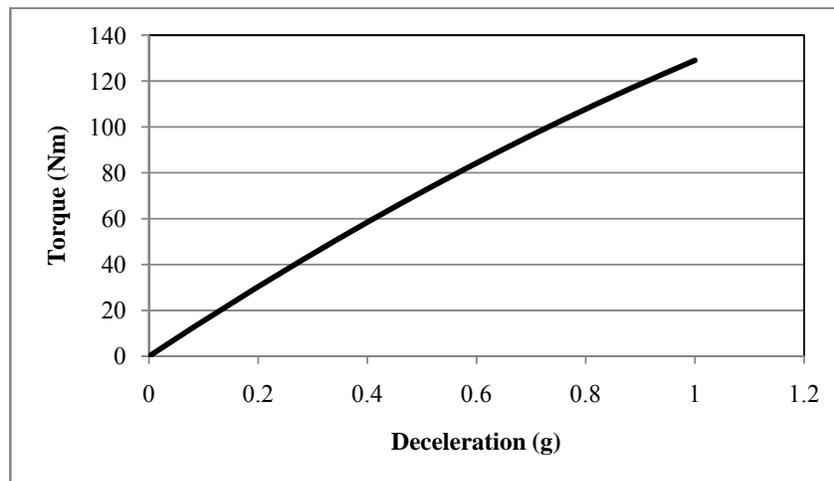
Thus, the ideal torque on the front and rear tyres can be determined using the ideal braking forces and the radius of the tyre, which can be worked out using the manufacturer's specified tyre dimensions. Figure 3.2 shows the ideal torque at the front and rear wheels as a function of deceleration. The data used to produce this graph is listed in Appendix A.



**Figure 3.2:** The ideal braking torque for the front and rear wheels of both the Lotus Elise and the REV Elise plotted against demanded deceleration.

Figure 3.2 shows that the front braking torques for both cars are almost identical. This means that no additional braking torque is required at the front. However, there is a large deficiency between the REV Elise rear braking torque and the Lotus Elise rear braking torque. This means that additional torque needs to be added at the rear in order to produce an optimum

system for the REV Elise. Thus, the regenerative braking at the rear will actually help the REV Elise achieve a more optimal braking distribution. In order to compare the necessary extra torque with the torque supplied by the motor, the difference is taken between the two rear torque curves and plotted against deceleration. This is shown in Figure 3.3 and data is listed in Appendix A.



**Figure 3.3:** The difference between the rear torque curves of the REV and Lotus Elise plotted against deceleration.

The curve in Figure 3.3 is a nearly linear line with a range of 0-129 Nm. The motor produces a braking torque of 0-240 Nm below base speed and a hyperbolically decreasing range above base speed. Base speed is 50km/h in 2<sup>nd</sup> gear and 80km/h in fourth. As the car drives at higher speeds, the braking distribution for a given deceleration will move closer to optimum range. In fourth gear, the motor will produce the optimum 0-129 Nm range at 155 km/h. For most driving speeds, however, the regenerative braking is adding additional torque at the rear above an optimal limit. Since excessive rear braking force can cause stability problems, it is necessary to analyse how the regenerative braking will affect the system as a whole. Figure 3.4 is plotted using the regenerative braking range of 0-240 Nm. This range is chosen because it is constant up to 80km/h, the hardest braking will occur during this range and the most energy will be recovered during this range. Figure 3.4 shows the optimal braking distribution and a linear line of best fit for this curve. The line of best fit represents the best friction braking distribution for a car with the parameters of the REV Lotus. Also plotted is the current friction braking distribution (REV Elise without regen). Lastly the braking distribution of the REV Lotus with regenerative with regenerative braking is plotted. This line is the friction

braking system plus the additional rear force due to the regenerative braking. The data for this graph is listed in Appendix A.

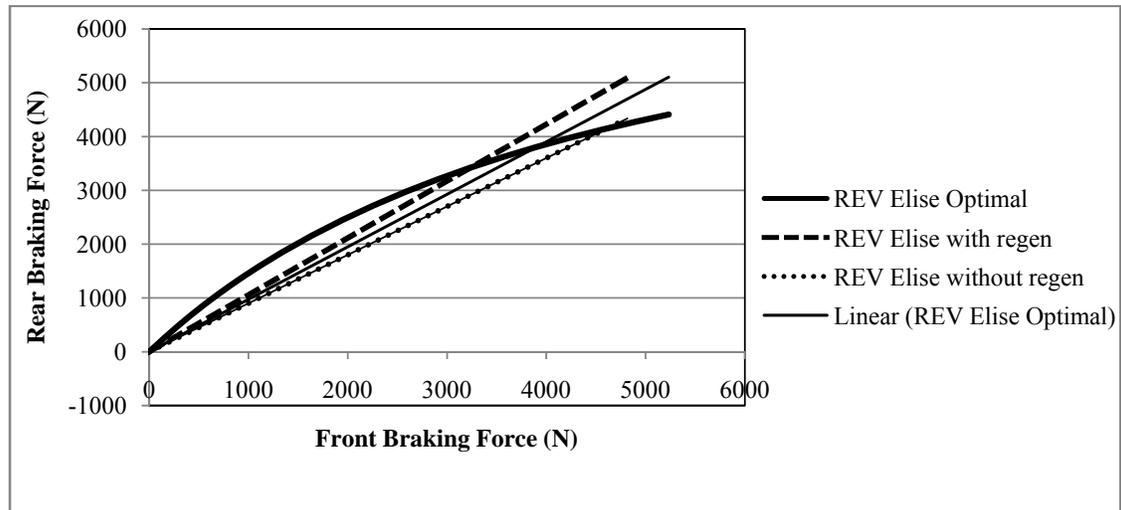


Figure 3.4: Braking force distribution comparison.

Recall from Section 2.2.2 that the intersection of a straight line and the curve of ideal braking distribution represents a specific road adhesive coefficient,  $\mu$ . If the linear force distribution line is below the ideal curve, the front wheels will lock up first under heavy braking.

Conversely, if the linear force distribution line is above the ideal curve, the rear wheels will lock up first. The closer the line is to the ideal curve, the better the braking forces will be distributed. The line of the REV Elise with regenerative braking gives the best approximation to the ideal curve below  $\mu$ , but the worst approximation above  $\mu$ . Recall that it is highly undesirable for the rear wheels to lock up since this will cause a loss of vehicle stability.

However, if the motor controller detects a stall, i.e. the rear wheels are locked, it will limit regenerative braking up to 50%. This means that if the rear wheels were to lock in the region above  $\mu$ , the force on the rear wheels would instantaneously drop and the braking distribution would approach the optimal curve. The regenerative braking acts like a natural ABS (Anti-lock Braking System). It detects wheel slip and restores control to the driver. In this way, the REV Elise with regenerative braking matches the optimum curve better than the frictional system alone, or the hypothetical linear distribution based on the ideal curve. Therefore, the regenerative braking system will make the car safer than if only the frictional braking system were used.

### *3.2.2 Analysis Conclusions*

Some important conclusions can be drawn from this analysis. Firstly, even though in most cars it is better to implement regenerative braking at the front wheels, there is no disadvantage in implementing the regenerative braking at the rear wheels of the Lotus. This is due to the weight distribution of the Lotus that causes the front and rear braking distribution to be almost the same. Secondly, the braking force required at the front of the car is practically the same for both the REV Elise and the Lotus Elise. However, additional force is required at the rear for the REV Elise. The regenerative braking is able to supply this additional force. Lastly, the regenerative system provides a much better approximation to the ideal braking curve than any purely hydraulic system. This means that the regenerative braking will make the REV Elise safer than if the standard frictional braking system was used alone.

## 3.3 Design of the regenerative Braking System

### *3.3.1 Regenerative Braking Control*

In order to activate the regenerative braking, the controller needs to receive an input signal between 0.5 and 4.5 volts. It will then translate this signal into a percentage of maximum negative torque and apply this torque to the rear wheels. The accelerator works in exactly the same way, except that it generates positive torque. The signals from the brake and accelerator effectively cancel each other out. It is important that the pedals do not produce a signal at the same time as this will cause an incorrect total braking or acceleration output torque. The maximum torque profile is the same for both positive and negative torque and is shown in Figure 2.5. In some situations it is desirable to modify this maximum torque curve. For example, a vehicle can stop too abruptly at slow speeds due to a large braking torque desired by the braking signal, and the inability of the drive system to actually reach this torque (UQM Technologies, Inc, 2009). Furthermore, the energy available for recovery at low engine speed is very low (Solberg, 2007). Thus, it may be best to limit the maximum torque in this range. The UQM motor controller allows for editing of the torque profile. By adjusting the maximum torque values at a given engine speed, it is possible to change the shape of the torque profile. An example of this is shown in Figure 3.5.

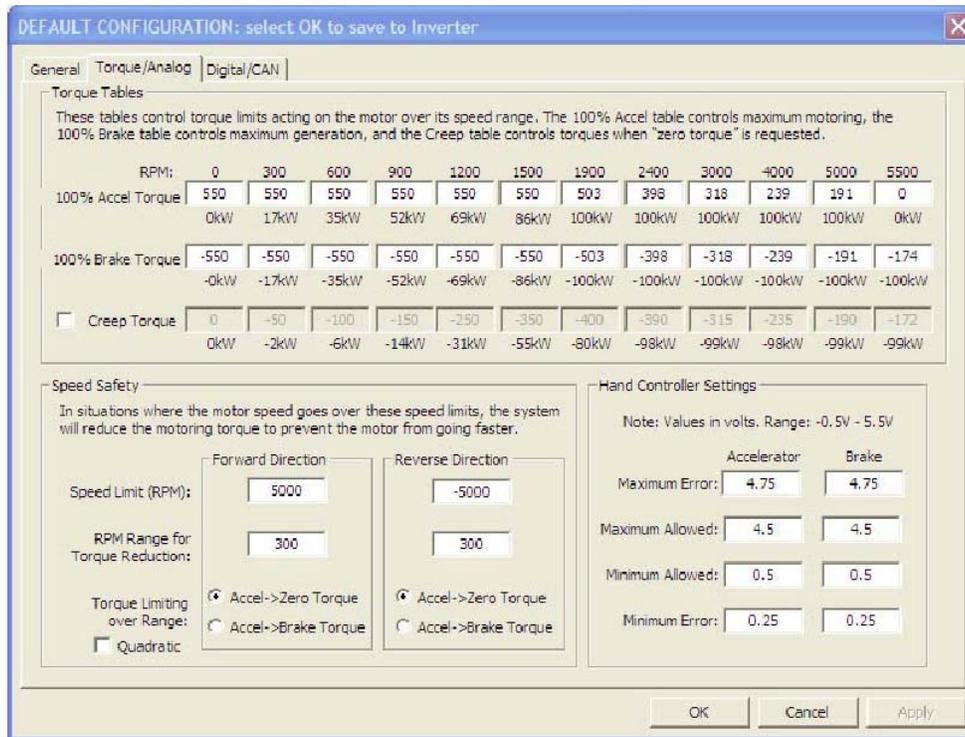


Figure 3.5: The brake, accelerator and creep torque control of the UQM motor controller software.

When neither the brake nor the accelerator is pressed, it is possible to use Creep Control to specify a default braking torque for this situation. This is how the engine braking will be simulated. Values for torque are entered over the engine speed range and a creep torque profile is generated. This will allow the driver to take advantage of regenerative braking with no energy being absorbed by friction braking.

### 3.3.2 Design Considerations

In certain critical situations, it is necessary that the regenerative braking be limited. It is very important that the regenerative braking does not produce a voltage or current that exceeds the maximum voltage or current of the motor, controller and batteries. Furthermore, if the batteries are fully charged, regenerative braking needs to be limited to prevent over-charging the batteries. As mentioned above, if the rear wheels were to lock, the regenerative braking needs to be limited to allow the driver to regain control. These are all critical situations that greatly affect the safety of the car. The motor controller is able to detect these situations and apply an appropriate limitation to the regenerative braking. The limitations that can be produced by the motor controller are summarised in Figure 3.6.

<b>Potential Regeneration Limitations</b>	
<b>Cause</b>	<b>Max. Limitation</b>
Over temperature (Inverter/Stator/Rotor)	25%
Motor Leg Current Over Current	27%
Bus Current Under Negative Current	24%
Bus Voltage Over Safety Voltage	1%
CTL_LINK analog signal set	50%
CAN control, no CAN communication	0%
Bad controller calibration	13%
Bad driver safety	40%
Stall conditions	50%
Current Sensors appear disconnected	24%
Bus Voltage over Customer Battery Max	2%
Incorrect position offset	36%
Error with Leg current sensors	35%
Invalid Sensor voltage	34%
Bus Voltage lower than optimum level	variable

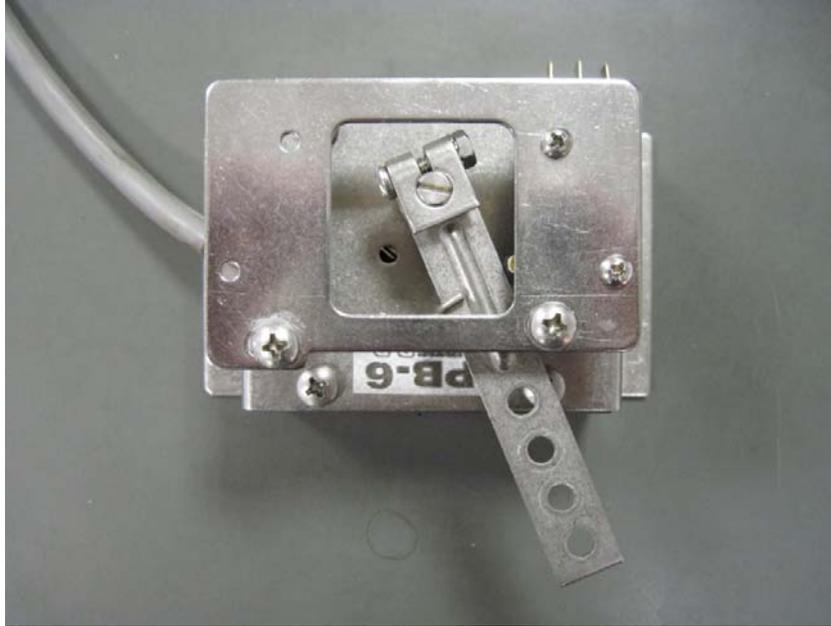
**Figure 3.6:** Limitations produced by the motor controller in critical situations.

[Image from: UQM Technologies, Inc (2009)].

### 3.3.3 Design of the braking and acceleration systems

Until now only the regenerative braking system has been mentioned. An additional part of this project is to design a system to link the accelerator to the motor controller. Accelerating the motor works in the same way as braking the motor – a 0.5-4.5 volt signal is sent to the controller and it translates this into a percentage of maximum torque and applies this to the wheels. The difference between the braking and accelerating torques is that the braking torque is negative, while the accelerating torque is positive.

For both the accelerator and the brake, a “pot box” will be used to generate the 0.5-4.5 V signal. A pot box is literally a box that contains a potentiometer. One of the pot boxes used in the installation is shown in Figure 3.7.



**Figure 3.7:** A pot box used to develop the 0.5-4.5 V brake or accelerator signal.

The pot box contains a potentiometer connected to a lever. The potentiometer is connected to three wires – Input, Output and Ground. The Input is a constant voltage that will be supplied via the motor controller. The output voltage is measured between Output and Ground and its value depends on the position of the lever. As the angle of the lever increases, the output voltage also increases. In order to allow the driver to brake or accelerate the car, the range of the brake/accelerator needs to be translated to the range of the pot box lever. In designing the system it was discovered that there were a few problems with this. Firstly, the pot boxes are too big to fit in the area behind the pedals and as a consequence they cannot be connected directly to the pedals. Furthermore, the range of the pedals does not match the necessary range of the pot box levers.

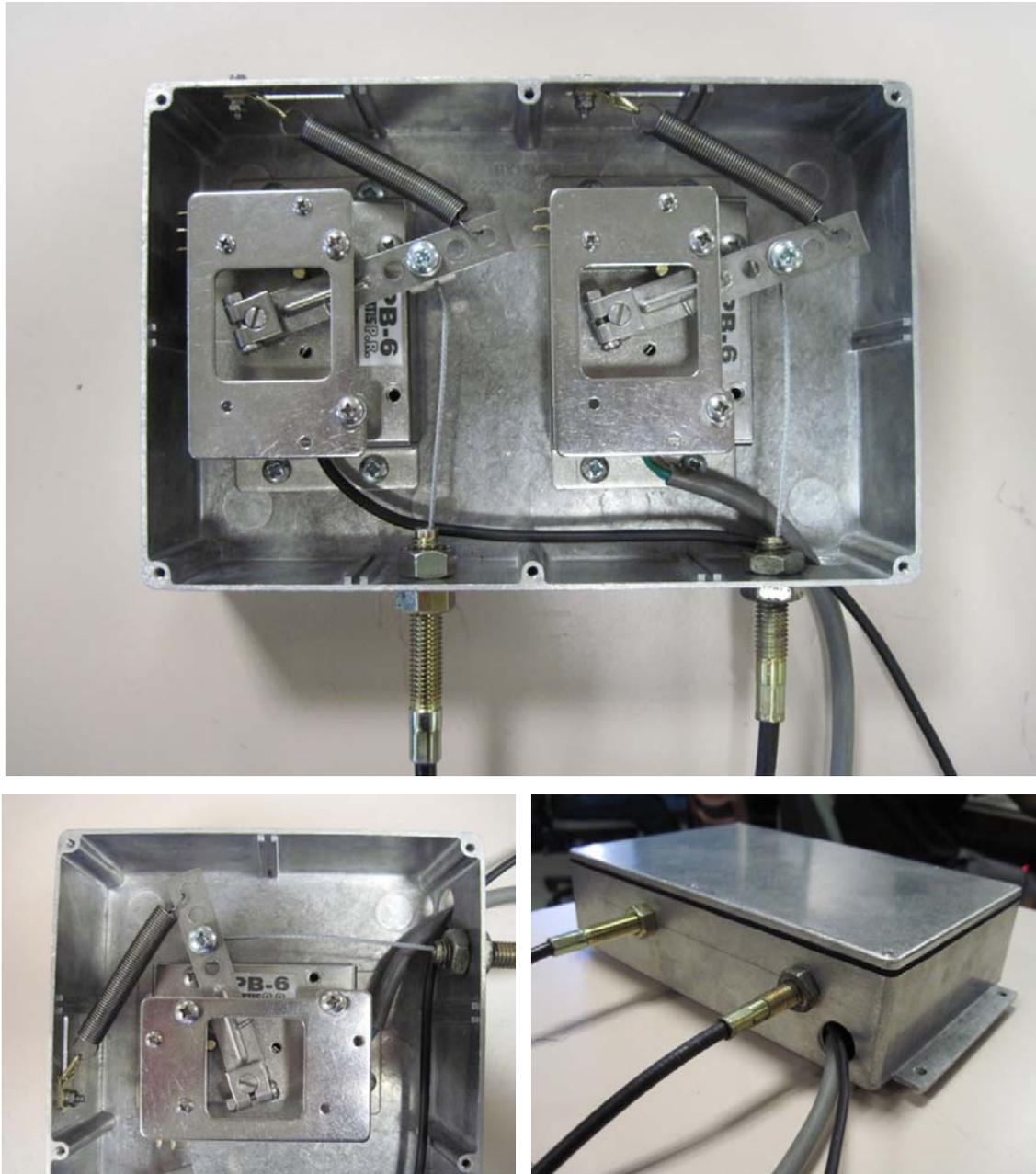
In order to solve these problems, the pedals will be connected to the pot boxes via cables. This allows the pot boxes to be placed at the rear of the vehicle where there is more space. There is also a need for a mechanical amplifying system to translate the range of the pedals to the range of the pot box levers. The accelerator of the car already had a cable and amplifying system, since it had to be connected to the original petrol motor at the rear. The range of this factory install amplifying system matched the range of the pot box on the second hole of the lever (note that the levers have four holes). The braking brake pedal is connected directly to the hydraulic master cylinder in the front of the car. In order to connect the brake pedal to the

pot box, a cable and amplifying system needed to be designed. This system consists of an adjustable amplifying lever, two mounts to secure the lever, and an adjustable rod and ball-and-socket joint system connecting the brake to the lever. It is necessary that the system contains a high level of adjustability because it was not possible to take exact measurements of the dimensions of components in the braking area. This is because there is an extremely small space in the pedal area and it was very difficult to read of manoeuvre measuring instruments in this area. This system required a number of custom parts to be manufactured. This includes a Pivot Plate, Cable Mount, Amplifying Lever, and Brake Pedal Clamp. The CAD drawings for all these parts, except the Cable Mount, are shown in Appendix B. The Cable Mount was practically the same as the factory installed Cable Mount for the accelerator. As such, it did not need to be redesigned. The cables from the pedals run through the centre console to the back of the car where they connect with the pot boxes. The pot boxes are housed in a die-cast aluminium box to protect them and to provide a base to mount the cables and pot boxes. In order to connect the nipple of the cable (a cylindrical piece of metal connected to the cable that acts as a stopper) to the pot box levers, a nipple mount needed to be designed. This design is shown in Appendix B.

When the pedals are not being pressed by the driver, it is important that they return to their original position so that they do not generate interfering signals. This means that the pot box lever must supply enough force on the cable to bring the pedal back into the original position. The pot boxes have torsion springs on them that provide some restoring force. To supplement this force, linear springs are connected between the die-cast box and the pot box levers to provide additional force.

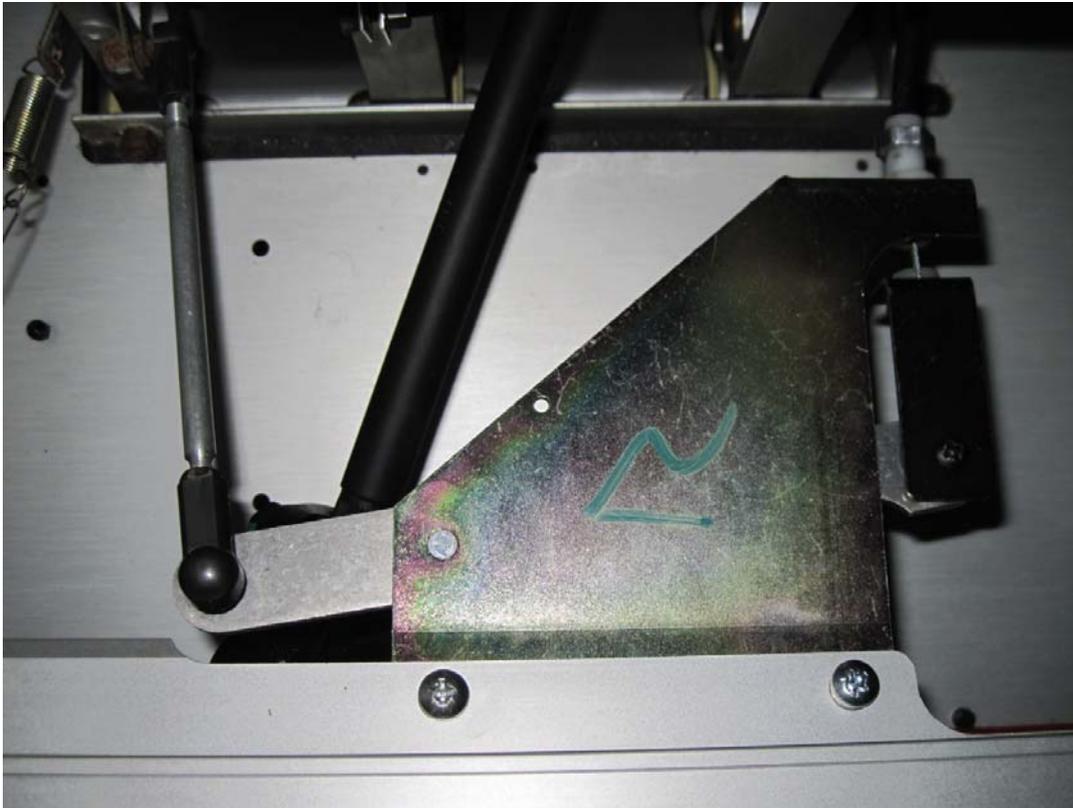
#### **4. Results and Discussion**

In order to construct the system, the custom parts were sent to a technician to be manufactured and all other parts were ordered from various suppliers. The parts that were ordered were the pot boxes, the braking cable, the ball-and-socket joints and the die-cast aluminium enclosure. All the parts for the pot box setup arrived in a timely manner and it was possible to construct this system. This is shown below in Figure 4.1.



**Figure 4.1:** Images of the pot box system. The braking cable is on the left and the accelerator is on the right. The input and output cables for each pot box are seen exiting the box in the bottom right hand corner.

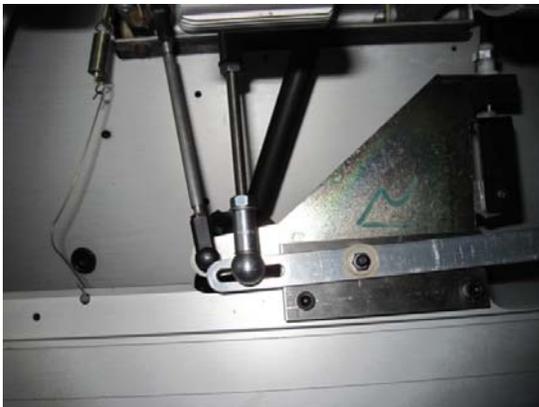
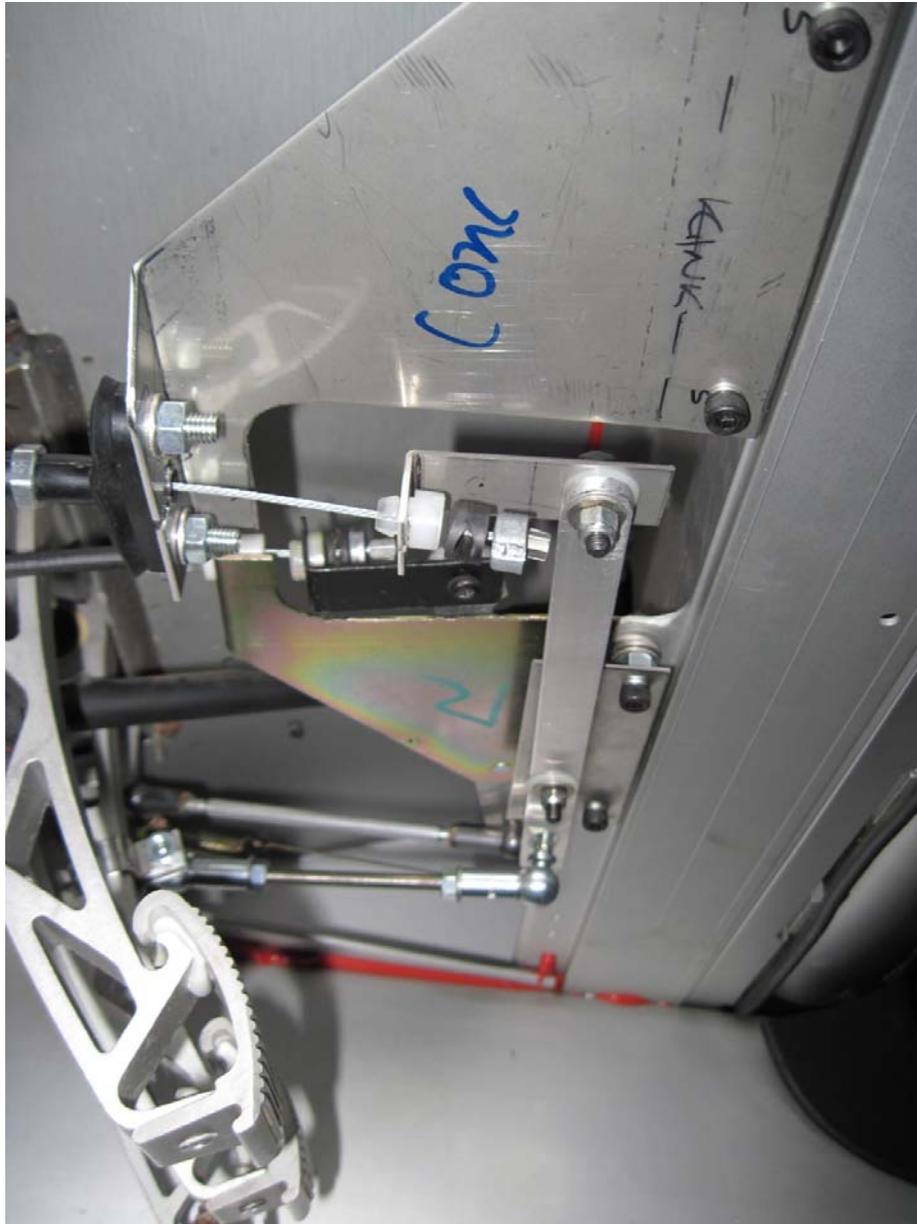
It was also possible to completely set up the accelerator system. Figure 4.2 shows the setup of the accelerator system before the braking system was installed.



**Figure 4.2:** The accelerator system. Accelerator is in top left and the cable running to the pot box is at the top right.

The accelerator system was tested and produced the correct range in the pot box. This means that the accelerator has successfully been transferred from controlling a petrol engine to controlling an electric engine.

The braking set up was then installed. Unfortunately, the ball-and-socket joints only arrived at midday on the day this report was due (even though they were ordered a week before). As such, it was not possible to fully adjust the system and test the range. However, it was possible to set the system up. The system appeared to be working effectively and no major design flaws were discovered. It will just take a few more hours to adjust the lever arm length so that the voltage at the pot box is in the range of 0.5-4.5 V. This will be done in the following week. Figure 4.3 shows some images of the braking and accelerator setup.



**Figure 4.3:** Images of the braking system as well as the accelerator system. All parts on the braking system were designed and manufactured for this project.

## **5. Conclusions and Future Work**

From the literature review it was determined that regenerative braking is an effective way to extend the range of an electric vehicle. The analysis showed that adding regenerative braking in a parallel system would enhance the braking of the car and make it safer at the same time. The design work was carried out effectively and the final system for both the brake and the accelerator worked well. The objective to install a regenerative braking system on the REV Elise was successfully attained.

The immediate future work is to fine tune the braking setup and test it with a multimeter to ensure that it delivers the correct output. Once the REV Elise is completed, the system will need to be tested while driving. It will then be possible to fine tune the parameters in the software to get the optimum combination of braking feel and energy recovery. An analysis should then be carried out to determine exactly how much energy is recovered and how far the regenerative system is able to extend the vehicle's range. Another small future task is to allow the regenerative system to be turned on and off at the touch of a button, within the car. At the moment, the regenerative braking can only be turned off by programming the motor controller with external software and setting all maximum torque values to zero.

In the long run, it would be a good project to try and implement a more advanced, series system on the REV Elise or another REV vehicle. This should allow for much more energy recovery as well as enhance the feel of the braking system and the safety of the vehicle.

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### Appendix A – Graph Data

Deceleration (g)	Deceleration (m/s)	Braking force front (N)	Braking force rear (N)
0	0	0	0
0.1	0.98	365	600
0.2	1.96	765	1164
0.3	2.94	1200	1693
0.4	3.92	1670	2187
0.5	4.9	2176	2646
0.6	5.88	2717	3069
0.7	6.86	3293	3457
0.8	7.84	3904	3810
0.9	8.82	4551	4128
1	9.8	5232	4411

**Table A.1:** The ideal braking forces of the REV Elise for a deceleration range of 0-1 g. Used for Figure 3.1.

Deceleration (g)	Deceleration (m/s)	Braking force front (N)	Braking force rear (N)
0	0	0	0
0.1	0.98	365	551
0.2	1.96	763	1068
0.3	2.94	1194	1552
0.4	3.92	1659	2003
0.5	4.9	2157	2420
0.6	5.88	2689	2803
0.7	6.86	3254	3153
0.8	7.84	3852	3470
0.9	8.82	4484	3754
1	9.8	5150	4004

**Table A.2:** The ideal braking forces for the Lotus Elise for a deceleration range of 0-1 g. Used for Figure 3.1.

Deceleration (g)	Deceleration (m/s)	Torque front (Nm)	Torque rear (Nm)
0	0	0	0
0.1	0.98	109	190
0.2	1.96	229	369
0.3	2.94	359	537
0.4	3.92	499	693
0.5	4.9	651	839
0.6	5.88	812	973
0.7	6.86	985	1096
0.8	7.84	1167	1208
0.9	8.82	1361	1309
1	9.8	1565	1398

**Table A.3:** The ideal braking torques of the REV Elise for a deceleration range of 0-1 g. Used for Figure 3.2.

Deceleration (g)	Deceleration (m/s)	Torque front (Nm)	Torque rear (Nm)
0	0	0	0
0.1	0.98	109	175
0.2	1.96	228	339
0.3	2.94	357	492
0.4	3.92	496	635
0.5	4.9	645	767
0.6	5.88	804	889
0.7	6.86	973	1000
0.8	7.84	1152	1100
0.9	8.82	1341	1190
1	9.8	1540	1269

**Table A.4:** The ideal braking torques of the Lotus Elise for a deceleration range of 0-1 g.

Used for Figure 3.2.

Deceleration (g)	Difference in rear torque (Nm)
0	0
0.1	15
0.2	30
0.3	45
0.4	58
0.5	72
0.6	84
0.7	96
0.8	108
0.9	119
1	129

**Table A.5:** The difference between the rear optimum torques of the Lotus Elise and the REV

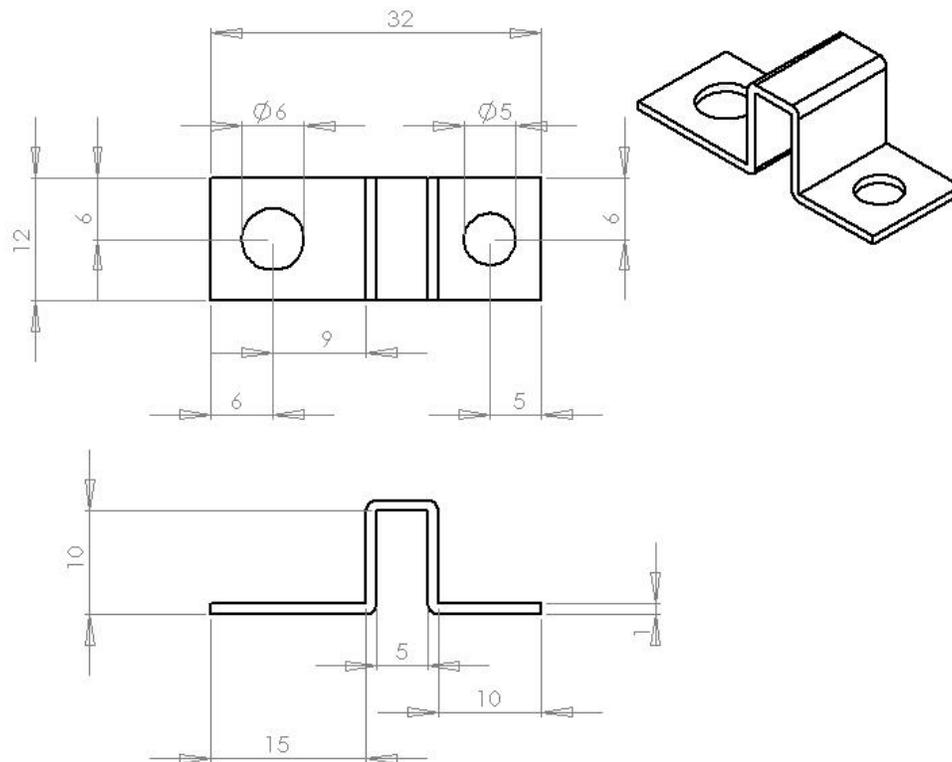
Elise. Used for Figure 3.3.

Deceleration (g)	Linear distribution of front force (N)	Linear distribution of rear force (N)	Force added by regen braking (N)	Total rear force (friction + regen) (N)
0	0	0	0	0
0.1	482	434	76	509
0.2	963	867	151	1019
0.3	1445	1301	227	1528
0.4	1927	1734	303	2037
0.5	2409	2168	379	2546
0.6	2890	2601	454	3056
0.7	3372	3035	530	3565
0.8	3854	3469	606	4074
0.9	4336	3902	681	4583
1	4817	4336	757	5093

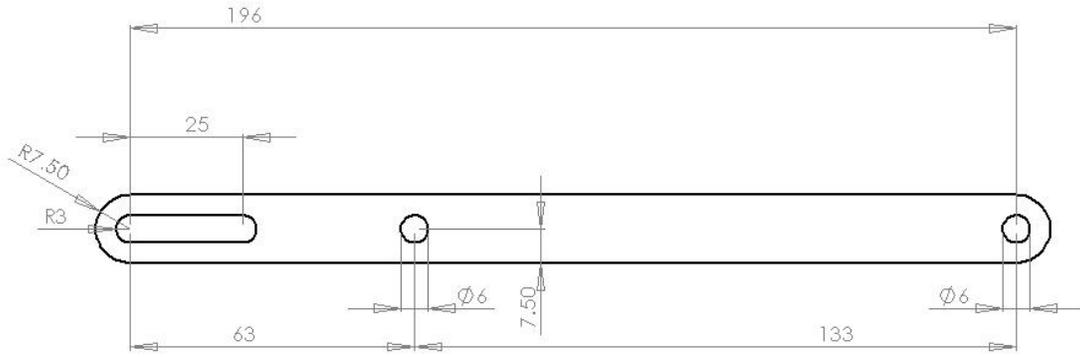
Table A.6: The linear distributions of braking force. Used for figure 3.4.

**Appendix B – CAD Drawings for Custom Parts**

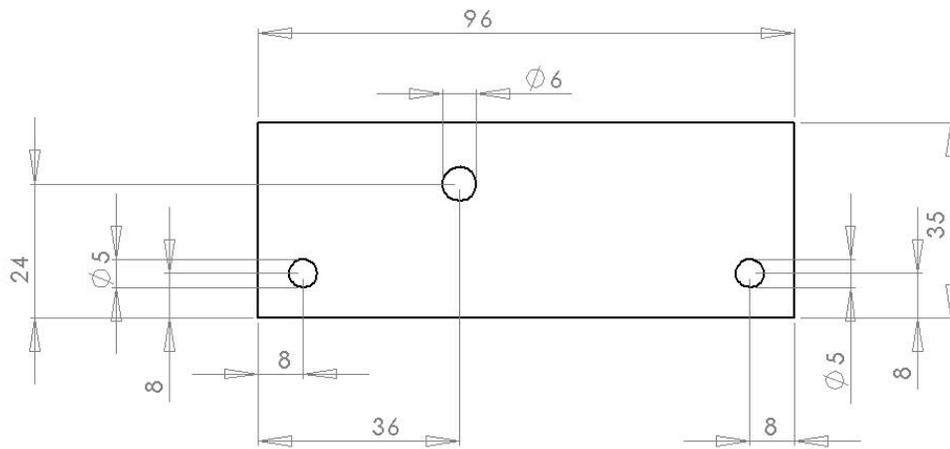
Note that all dimensions are in millimetres.



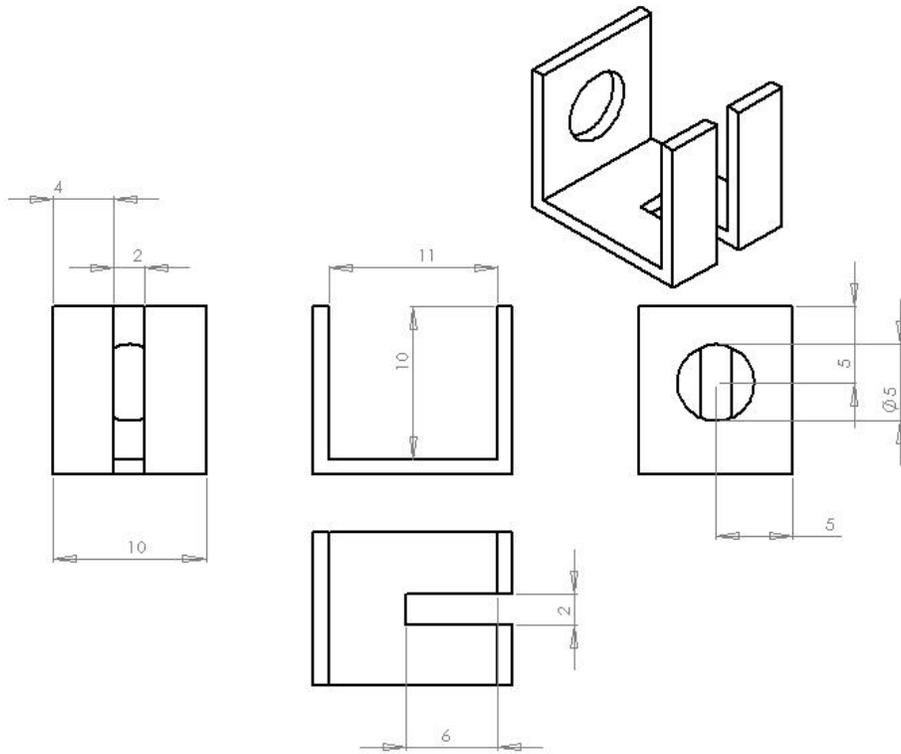
**Figure B.1:** Brake Clamp. Material is 1 mm thick steel.



**Figure B.2:** Amplifying Lever. Material is 4mm thick aluminium.



**Figure B.3:** Pivot Plate. Material is 1.5 mm thick steel.



**Figure B.4:** Nipple Mount. Material is 1.5 mm thick square tube aluminium.