



# Optimizing the mechanical packaging of drivetrain components in Formula Student battery electric vehicles

Development of electric drivetrains for student engineering competition

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Optimering av mekanisk paketering av drivlina i batteridrivna elektriska Formula Student fordon

Utveckling av elektriska drivlinor för ingenjörstävling för studenter

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# Abstract

The world has seen a rapid increase in the development of electric vehicles. This development is made possible by competent engineers. Formula Student competitions offer engineering students the opportunity to not just get a head start in knowledge on how to develop electric vehicles but also get the opportunity to try out new concepts and technologies that may not yet be widely adopted.

In a highly competitive environment, such as motorsports, the motivation to optimize and innovate is great. By reducing weight and inertia teams can greatly increase the performance of their vehicles. A lot of effort is made to optimize existing parts and concepts, but the best strategy for reducing mass and inertia is to eliminate the need for a part or a system altogether. By rethinking how the drivetrain of a Formula Student vehicle is packaged and interconnected, significant mass and inertia savings can be made. This is, however, often a difficult process that requires a lot of problem solving in many different engineering disciplines such as: electromechanics, electromagnetics, thermodynamics, mechanical design, material science and electronics.

This thesis concludes that the most performant vehicle configuration is to utilize four-wheel drive as this allows for far better utilization of the available traction. Several ideas and concepts on how the packaging of drivetrain can be optimized are detailed and discussed. One concept calls for the design of a custom electrical machine, a rough estimation of which is done using analytical methods. These concepts are then compared to an existing drivetrain concept. It is concluded that the concept that is presented needs more work if it is to ever become a viable solution.

# Abbreviations

<b>2WD</b>	Two-wheel Drive
<b>4WD</b>	Four-wheel Drive
<b>AWD</b>	All-wheel drive
<b>CAD</b>	Computer Aided Design
<b>CRR</b>	Clear River Racing
<b>CRRXX</b>	Clear River Racing 20XX (team or car from 20XX)
<b>EMF</b>	Electro Motive Force
<b>FEA</b>	Finite Element Analysis
<b>FS</b>	Formula Student
<b>FSG</b>	Formula Student Germany
<b>FSUK</b>	Formula Student UK
<b>FWD</b>	Front-wheel Drive
<b>MCM</b>	Magnetic Circuit Model
<b>PM</b>	Permanent Magnet
<b>PMSM</b>	Permanent Magnet Synchronous Machine
<b>RWD</b>	Rear-wheel Drive

# Symbols

$A$	RMS linear current density [ $A/m$ ]
$B_{PM}$	flux density in permanent magnet at loading point [ $T$ ]
$B_r$	remanent flux density of permanent [ $T$ ]
$\hat{B}_\delta$	peak flux density [ $T$ ]
$\hat{B}_{ry}$	peak reference flux density in rotor yoke [ $T$ ]
$\hat{B}_{st}$	peak reference flux density in stator teeth [ $T$ ]
$\hat{B}_{sy}$	peak reference flux density in stator yoke [ $T$ ]
$D_r$	rotor diameter [ $m$ ]
$E$	energy [ $J$ ]
$E_m$	electro motive force [ $V$ ]
$g$	gear ratio $[-]$
$h_{PM}$	height of permanent magnet [ $m$ ]
$h_{ry}$	height of rotor yoke [ $m$ ]
$h_{sy}$	height of stator yoke [ $m$ ]
$I$	current [ $A$ ]
$\mathbf{I}$	inertia [ $kg \times m^2$ ]
$J$	current density [ $A/m^2$ ]
$l_r$	rotor length [ $m$ ]
$l_s$	stator length [ $m$ ]
$l'_r$	equivalent rotor length [ $m$ ]
$l'_s$	equivalent stator length [ $m$ ]
$k_w$	winding factor $[-]$
$k_{Fe}$	iron space factor $[-]$
$k_{Cu}$	copper space factor $[-]$
$N_{c,slot}$	number of conductors per slot $[-]$
$N_{phases}$	number of phases $[-]$
$N_{poles}$	number of poles $[-]$
$N_{slots}$	number of slots $[-]$
$N_{turns,phase}$	number of turns per phase $[-]$
$N_{  }$	number of parallel paths $[-]$
$n$	rated speed [ $RPM$ ]
$m$	mass [ $kg$ ]
$P$	rated power [ $W$ ]
$r$	radius [ $m$ ]
$r_r$	rotor radius [ $m$ ]
$S_c$	cross-sectional surface area of single conductor [ $m^2$ ]
$S_r$	rotor surface area (idealized as perfect cylinder) [ $m^2$ ]
$S_{slot}$	cross-sectional surface area of single slot [ $m^2$ ]
$T_{max}$	maximum torque [ $Nm$ ]
$U$	rated voltage [ $V$ ]
$U_s$	terminal voltage [ $V$ ]
$\hat{U}_{m,\delta}$	magnetic voltage in air gap [ $A$ ]
$\hat{U}_{m,ry}$	magnetic voltage in rotor yoke [ $A$ ]
$\hat{U}_{m,st}$	magnetic voltage in stator teeth [ $A$ ]
$\hat{U}_{m,sy}$	magnetic voltage in stator yoke [ $A$ ]
$v$	velocity [ $m/s$ ]
$w_{st}$	width of stator tooth [ $m$ ]
$\alpha_i$	saturation factor $[-]$
$\delta$	air gap length [ $m$ ]
$\eta$	efficiency $[-]$

$\mu_{PM}$	permeability of permanent magnet [ $H/m$ ]
$\xi$	ratio between component rotational speed and vehicle linear speed [–]
$\sigma_{F,tangential}$	tangential stress [ $Pa$ ]
$\tau_p$	pole pitch [ $m$ ]
$\tau_s$	slot pitch [ $m$ ]
$\hat{\phi}_m$	peak pole flux [ $Wb$ ]
$\omega$	rotational velocity [ $rad/s$ ]

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# 1. Introduction

## 1.1. Background

### 1.1.1. Formula Student

Formula Student (FS) is a series of global competitions where teams of university students compete against each other by designing and building small formula style race cars (see Figure 1.1). For teams competing in Europe there are essentially two sets of rules: one set published by IMechE<sup>1</sup>, which is used by the FSUK (Formula Student UK) competition [1], and one set published by FSG (Formula Student Germany) used for the FSG competition [2] and many others, including: FS East<sup>2</sup>, FS Czech<sup>3</sup>, FS Netherlands<sup>4</sup>, FS Alpe Adria<sup>5</sup> and FS Austria<sup>6</sup>. These competitions use the FSG rules with only minor changes and additions specified in competition specific handbooks.

### 1.1.2. Clear River Racing

Clear River Racing is a Formula Student team at Karlstad University, Sweden. The team was established in 2007 and competed for the first time at the Formula Student UK competition in 2008. The team has produced a new car every year since then, most of them being powered by internal combustion engines, though the team switched to producing battery electric vehicles in time for the 2021 competition season. In this text the team's latest vehicle, the CRR23 (see Figure 1.1) will be used as a point of reference when discussing alternative



drivetrain solutions.

*Figure 1.1: The CRR23 vehicle on release day.*

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<sup>1</sup> <https://osf.imeche.org/>

<sup>2</sup> <https://fseast.eu/>

<sup>3</sup> <https://fsczech.cz/>

<sup>4</sup> <https://www.formula-student.nl/>

<sup>5</sup> <https://fs-alpeadria.com/>

<sup>6</sup> <https://fsaustria.at/>



## **1.2. Purpose**

The purpose of this thesis is to investigate the possibilities of optimizing the mechanical packaging of the drivetrain for battery electric formula student vehicles. This includes everything from, but not including, the inverters, all the way out to the wheels. The goal is to first specify reasonable performance requirements for the powertrain, then conceptualize solutions that match these requirements and do so in an efficient manner. The drivetrain concept used for CRR23 will be used as a baseline reference when optimizing these new concepts. Since the new performance requirements may differ from the target performance of the CRR23 drivetrain, the optimization will focus on torque densities (torque measured at the wheels) as this results in a fairer comparison.

## **1.3. Delimitations**

The concepts delivered as a result of this thesis will at most be presented on a principal level with estimations of initial designs as designing fully operational concepts would take far too much time. A portion of this thesis covers electric machine design, for this, no transient finite element analysis (FEA) has been carried out due to lacking access to software capable of such analysis. Also, only active components of the electric machine will be considered in this text, this excludes things like bearings, insulation system, cooling and housings.

## **2. Theory**

### **2.1. Drivetrain Configurations**

In this section different drivetrain configurations will be discussed. Including different options for power sources, driven wheel configurations and options for power transmission. The discussion will focus on what is allowed and possible within formula student vehicles.

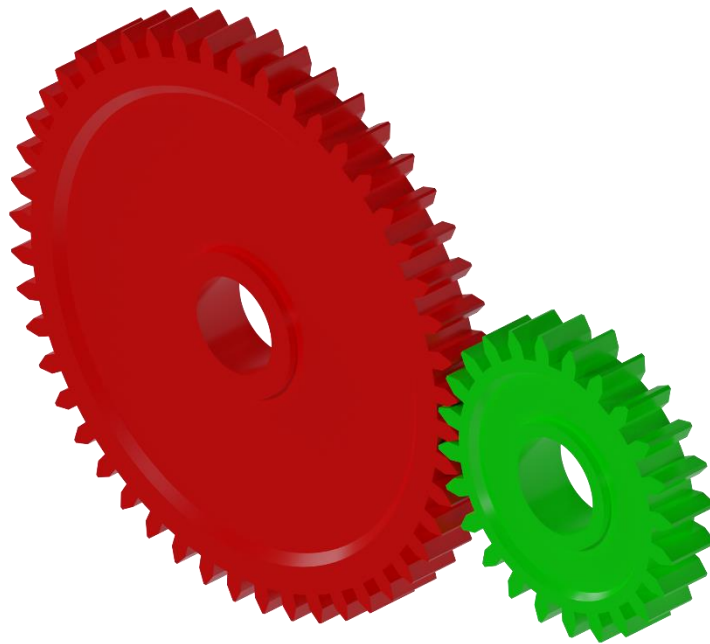
#### **2.1.1. Power Sources & Gearing**

One major component of any drivetrain is the power source or sources. In formula student competitions, the vehicles may be powered by virtually any power sources. The most common options are internal combustion engines, running on gasoline or ethanol, or electric motors, powered by an onboard battery, or a hybrid of these. If one wishes to compete with any other type of fuel or power source one must submit an extra document to the competition judges detailing this alternative fuel. The judges then decide whether you are eligible to compete with the specified fuel or not. Though there are several reasons why one would choose to go with one type of power source over another, this text will only consider electric drivetrains, using one or more electric machines powered by an onboard battery.

One clear benefit of electric machines, as opposed to combustion engines, is that electric machines (usually) exhibit a high constant torque over a large range of speeds [3]. This has the benefit of not requiring multiple different gearing ratios, between the machine and the wheels, to maintain optimal torque as the speed changes [4]. An electric machine may however still need a constant gearing ratio to achieve appropriate torques and speeds for a traction application. This is because most electric machines are often designed to be operated at high speeds and thus usually have rather low torque in comparison to what is desirable for use in a vehicle. This gearing ratio can be achieved in a number of different ways, some of which will now be discussed. Throughout this discussion it will be assumed that any gearing that is required needs to decrease speed and increase torque.

### 2.1.1.1. Meshing Gears

One way to achieve a constant gearing ratio is to use different sized meshing gears. This can also be done in a number of different ways depending on the types of gears used but most commonly spur gears would be used for this type of application (see Figure 2.1). Besides implementing gearing this also comes with a few other consequences which may or may not be desirable. One consequence is that the input axis and output axis, on this type of solution, would not be coaxial. Which can be beneficial or a problem depending on other aspects of the vehicle. This is of course hugely dependent on what gearing ratio is required, the geometry and size of the machines used, and where there is available space in the vehicle. Even though it is often undesirable that the input and output shafts of a solution like this are not coaxial, it can be utilized beneficially. It does for example allow for the possibility of mounting the machines lower in the vehicle, lowering the center of gravity, and using the offset between the input and output axis to get the rotation to the center axis of the wheel. Using bevel gears also opens up the possibility of introducing an angle between the input and output axis which in turn opens up more possibilities when it comes to mounting the machine(s) in relation to the vehicle. Any type of solution incorporating gearing like this would most probably add quite a bit of weight and would take up a fair amount of space compared to other alternatives capable

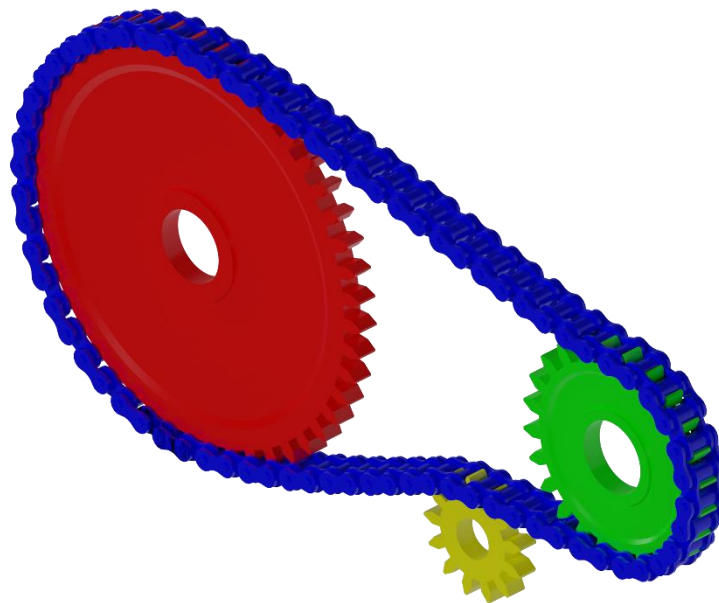


of achieving the same gearing [4] [5].

*Figure 2.1: Spur gears with two gears of different sizes, 48 teeth (red) and 24 teeth (green), respectively.*

### 2.1.1.2. Chain/Belt

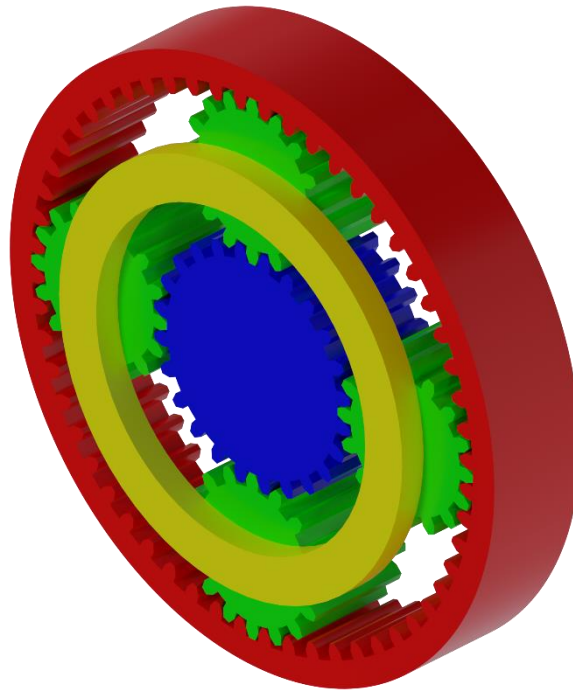
Another way to achieve a constant gearing ratio, which is very similar to meshing gears, is to use a chain and sprockets or a belt and pulleys. In principle these two solutions function in much the same way and have similar benefits and drawbacks. One benefit of this type of solution, over meshing gears, is that the sprockets/pulleys do not have to be in direct contact with each other but are instead connected via the chain or belt (see Figure 2.2). This allows for more flexibility when placing the input and output axis as the length of the chain or belt can be selected to fit virtually any spacing. This type of solution does however require some other additional components in the form of chain/belt tensioning to function properly, which of course, adds mass and complexity. Similar to meshing gears, a solution incorporating chains or belts like this this would most probably add quite a bit of weight and would consume a fair amount of space [4] [5].



*Figure 2.2: Chain drive including two primary sprockets (red & green), chain (blue) and sprocket for tension (yellow).*

### 2.1.1.3. Epicyclic/Planetary Gearing

The final way to achieve a constant gearing ratio that will be discussed here is the epicyclic or planetary gearbox. A planetary gearbox consists of four main parts. The ring gear, the sun gear, the planet gears and the carrier (see Figure 2.3). The ratios between the different gears and which combination of parts (ring gear, sun gear, carrier) is driven, driving and fixed determines the final gear ratio of the gearbox. Benefits of a planetary gearbox include: a very compact design with low mass and inertia as well as the output axis being coaxial with the input axis, allowing for compact packaging when considering the drivetrain as a whole [4].



*Figure 2.3: Planetary gearing with ring gear (red), sun gear (blue), planet gears (green) and carrier (yellow).*

## **2.1.2. Number of Driven Wheels**

One way in which drivetrains are classified is by the number of driven wheels and which of the wheels are driven. This becomes quite an extensive topic when considering all possible combinations of driven and non-driven wheels for all types of vehicles incorporating varying numbers of wheels. Therefore, and because this is a requirement for formula student vehicles, only vehicles with a total of four wheels will be discussed in this text.

When all four wheels are driven, it is referred to as an AWD (all-wheel drive) or a 4WD (four-wheel drive) vehicle. When only two of the wheels are driven, the vehicle is referred to as a 2WD (two-wheel drive) vehicle. These vehicles are however usually more commonly denoted by which set of wheels are driven. Being referred to as a FWD (front-wheel drive) vehicle if the two front wheels are driven and a RWD (rear-wheel drive) if the two rear wheels are driven. One could imagine a vehicle with one driven wheel in the front and one driven wheel in the rear, which would classify it as a 2WD, though this is very rare in practice for various reasons. One being torque and mass imbalance. There are also 1WD (one-wheel drive) vehicles, which are also rather rare for similar reasons.

When it comes to formula student vehicles in particular the most common configuration historically has been RWD vehicles. When using an internal combustion engine this is the clear choice. The form factor of formula student vehicles often makes it difficult to achieve FWD vehicles with internal combustion engines since the engine is almost always mounted in the rear, behind the driver, and transmitting the torque to the front wheels is thus made difficult, if not impossible, to achieve in a space and mass efficient manner. However, as more teams are switching to electric drivetrains, they are also producing more vehicles with 4WD/AWD drivetrains, something which is much more easily achievable with electric drivetrains. Being able to drive the wheels directly at the wheels, using hub motors, and not having to use drive shafts to transmit torque from a central power source is what has really opened up the possibility of driven front wheels for formula student vehicles. Despite this most electric formula student cars are either RWD or 4WD/AWD.

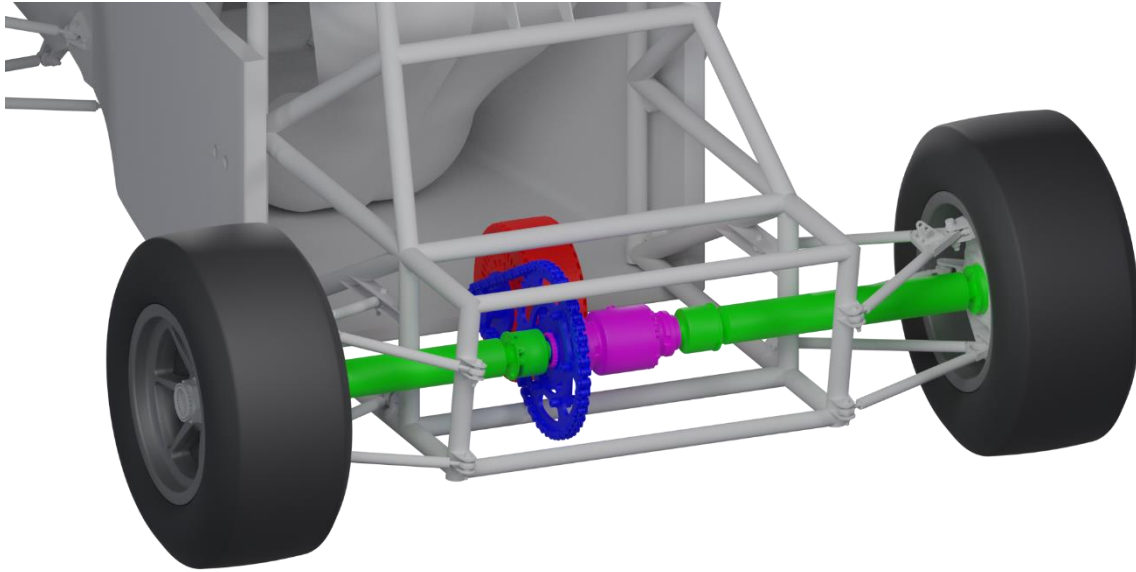
## **2.1.3. Power Transmission**

The previous discussion on driven wheels does not consider how power can be transmitted from a power source to the driven wheels. This can be achieved in a number of different ways, all with their own benefits and drawbacks, some of the possible solutions, used within formula student vehicles, will be discussed in the following sections.

### **2.1.3.1. Chain/Belt Drive and Differential**

Pretty much all combustion engine formula student vehicles have the engine mounted in the rear of the chassis. The engine is then connected to a differential by a chain and sprockets, alternatively by a belt and pulleys. This naturally introduces a chance for gearing the output of the engine. From the differential, power is transmitted to the driven wheels using drive shafts (see Figure 2.4). This has the benefit of being able to power two wheels using one engine, and the use of a differential allows for the inner and outer wheel to rotate at different velocities which is hugely beneficial in cornering. It also means that the amount of unsprung mass can be kept relatively low.

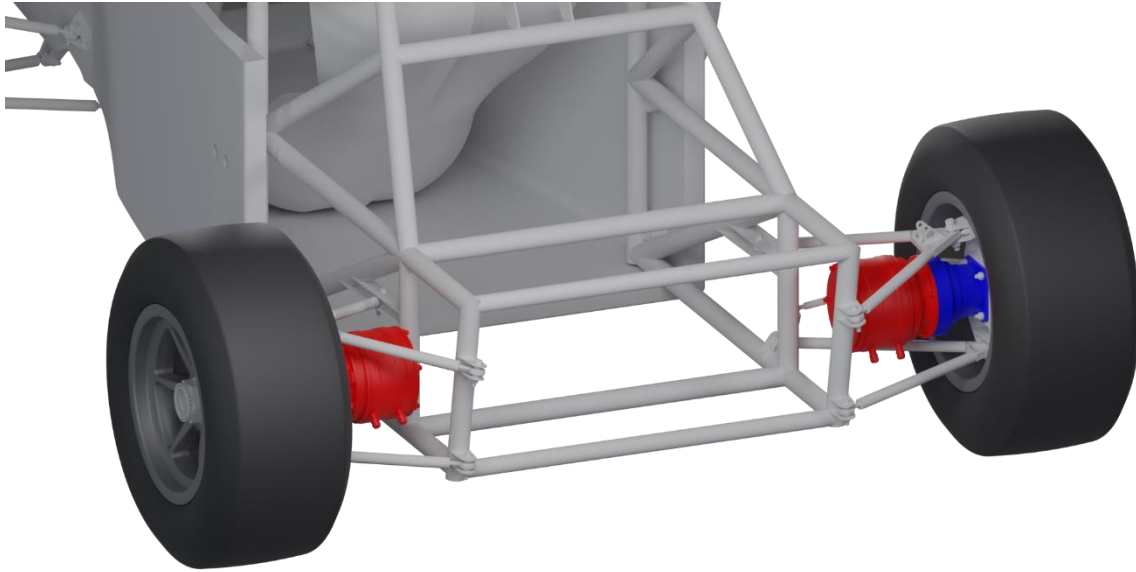
Many formula student teams switching to electric drivetrains use this configuration as it closely mimics their previous configuration, they simply replace the combustion engine with an electric machine (and make space for a big battery pack somewhere on the vehicle).



*Figure 2.4: Illustration of formula student vehicle with chain drive and differential drivetrain configuration, showing central motor (red), chain drive (blue), differential (pink) and drive shafts (green).*

### **2.1.3.2. Hub Motors**

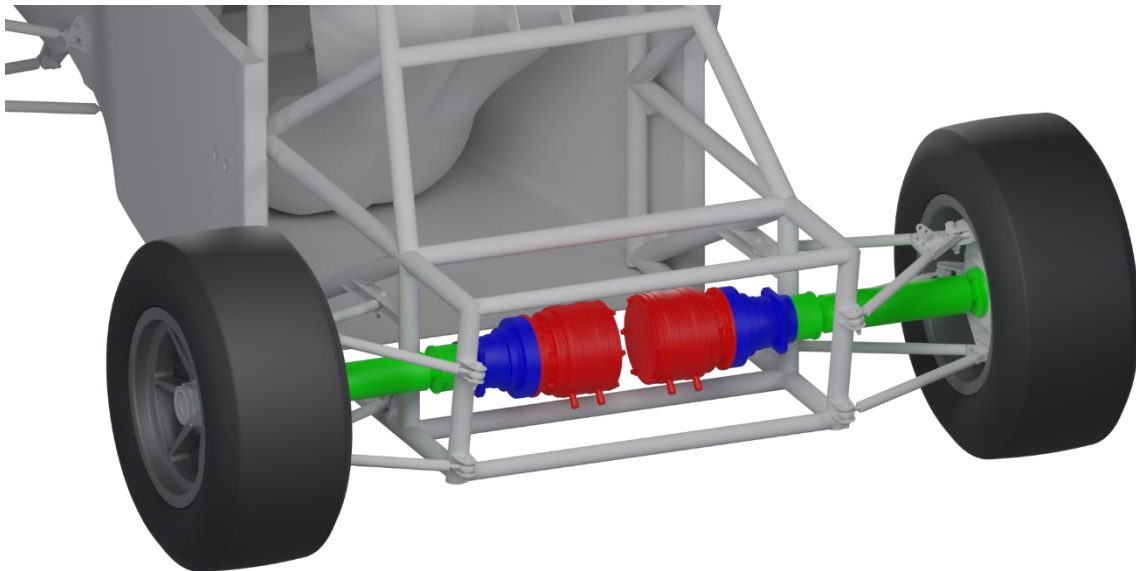
Using an electric drivetrain opens up the possibility for hub motors. Which is where electric machines are mounted directly to the hubs of the car (see Figure 2.5). So, for example: instead of using one big motor to power two wheels, two smaller motors are used to power each wheel independently. This can also rather easily be extended to four wheels and four motors, which is a common configuration for high performing electric formula student teams. One benefit of having one motor per wheel is the amount of control this offers. Whereas a differential is (in most cases) completely mechanical and doesn't offer any dynamic control, a motor can always be told what to do. This allows for something called torque vectoring, where the torque applied at each driven wheel is precisely controlled which makes it possible to direct the power to the wheels which have the most grip at the given moment i.e., where it is as most useful. One downside to hub motors is that you add extra unsprung mass by placing the motors out at the wheels and not in the chassis. Placing the motors at the wheels does mean that space is freed up in the chassis, making it easier to fit the batteries, inverters and other electronics. Another disadvantage of hub motors is that each motor (usually) requires their own gearbox or other type of gearing to achieve reasonable speeds and torques.



*Figure 2.5: Illustration of formula student vehicle with hub motor configuration, showing motors (red) and gearboxes (blue).*

### **2.1.3.3. In-board Motors**

As mentioned in the previous two sections there are benefits both to having your motor(s) mounted in the chassis of the vehicle, and having multiple motors, each powering a single wheel. Seeking to find a middle ground between these two approaches, in-board motors can be used. This entails having multiple motors mounted in the chassis, each connected to a single wheel using drive shafts (see Figure 2.6). This keeps the unsprung mass low and allows for electrically controlled torque vectoring. However, it may still be difficult to package a solution like this in a compact way.



*Figure 2.6: Illustration of formula student vehicle with in-board motor configuration, showing motors (red), gearboxes (blue) and drive shafts (green).*



## 2.2. Mechanics

When optimizing mechanical components, the goal is often to decrease the mass of the component. For rotating components, not only does the mass of the object matter, but also where that mass is placed in relation to the axis of rotation, i.e., the inertia of the object. This means that there are many ways to optimize a rotating component. The best possible scenario would be to decrease the mass, the inertia and the speed at which the component will rotate. Achieving all of this at the same time is often difficult (assuming the component is not horribly designed to begin with). To compare different mechanical solutions, it can therefore be advantageous to combine these properties into one comparable quantity. This is where the concept of equivalent mass comes in, which will be explained in the next sections following an introduction to energy equations.

### 2.2.1. Energy

The translational kinetic energy of an object is described by:

$$E = \frac{1}{2}mv^2 \quad (2.1)$$

where:

- ◁  $m$  is the mass of the object [ $kg$ ]
- ◁  $v$  is the linear speed of the object [ $m/s$ ]

The rotational kinetic energy of an object is described by:

$$E = \frac{1}{2}I\omega^2 \quad (2.2)$$

where:

- ◁  $I$  is the moment of inertia of the object [ $kg \times m^2$ ]
- ◁  $\omega$  is the angular speed of the object [ $rad/s$ ]

Combining equations (2.1) and (2.2) gives the total kinetic energy of an object:

$$E = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \quad (2.3)$$

Thus, by summing the kinetic energy of every single component, the total energy of a vehicle could be described as:

$$E = \sum_i \frac{1}{2}m_i v_i^2 + \frac{1}{2}I_i \omega_i^2 \quad (2.4)$$

It then becomes clear that for a vehicle traveling at a speed  $v$  ( $v_i \approx v$ ), the energy required to reach that speed, can be decreased. For non-rotational components ( $\omega_i = 0$ ) by decreasing their mass. And for rotational components ( $\omega_i > 0$ ) by decreasing their moment of inertia and/or rotational speed (in a way that does not also affect the linear speed of the vehicle).

### 2.2.2. Equivalent Mass

For rotational components that are a part of the drivetrain the rotational speed of the component is proportional to the linear speed of the vehicle. This is not strictly true as there are plenty of scenarios where the rotational speed of particular components is not proportional to the linear speed of the vehicle, such as during wheel slip, cornering, or when a vehicle incorporates clutches, and these are disengaged. However, on average, and during normal

driving conditions, this relationship holds true. The ratio between the rotational speed of a component and the translational speed of the vehicle is thus:

$$\xi_i = \frac{\omega_i}{v} \quad (2.5)$$

where:

- ◁  $\xi_i$  is the ratio between the rotational speed of the component and the linear speed of the vehicle [rad/m]

The ratio  $n$  depends on the radius of the tire the component is connected to and any gearing ratios between the component and the tire, and can thus be calculated using the following equation:

$$\xi_i = \frac{g_i}{r_i} \quad (2.6)$$

where:

- ◁  $r_i$  is the radius of the tire connected to the component [m]
- ◁  $g_i$  is the total gear ratio between the tire and the component [-]

Combining equation (2.3) and (2.5) gives:

$$E = \frac{1}{2}mv^2 + \frac{1}{2}I\xi^2v^2 \quad (2.7)$$

By introducing a new quantity,  $m_e$ , referred to as “equivalent mass” equation (2.7) can be rewritten as:

$$\frac{1}{2}m_e v^2 = \frac{1}{2}mv^2 + \frac{1}{2}I\xi^2v^2 \quad (2.8)$$

Eliminating common factors gives:

$$m_e = m + I\xi^2 \quad (2.9)$$

This relationship makes it easy to compare what impact different components will have on the acceleration and efficiency of a vehicle [6] [7].

## 2.3. Electrical Machines

In this section the basics of rotational electrical machines will be introduced. Rotating electrical machines utilize changing magnetic fields to generate the torque needed to achieve rotation. These magnetic fields can be the result of either permanent magnets or electromagnets, commonly referred to as coils or windings. Electrical machines can operate as both motors (turning electrical energy into kinetic energy) and generators (turning kinetic energy into electrical energy). There exist multiple types of rotating electrical machines but on a fundamental level they all consist of two basic components:

- ◁ Stator
- ◁ Rotor

These components work differently in different types of electrical machines, but in all types of electrical machines they experience relative rotational motion. The geometric relationship between the stator and the rotor of an electrical machine is one classification that can be made to differentiate between electrical machines. When the rotor is inside of the stator the machine is referred to as an “in-runner” machine and when the rotor is outside of the stator the machine

is referred to as an “out-runner” machine (see Figure 2.7). On a theoretical level, and without specifying the details of these two components, this distinction may seem arbitrary, as which part is the stator and which is the rotor, is simply a definition of which part is considered static and which is considered to be rotating in comparison to a reasonable reference frame. In practice this distinction does however become very much tangible, as rotating the component which has been designed to be the stator, and which thus have the supply cables coming out of it, is (for hopefully obvious reasons) generally considered a bad idea.

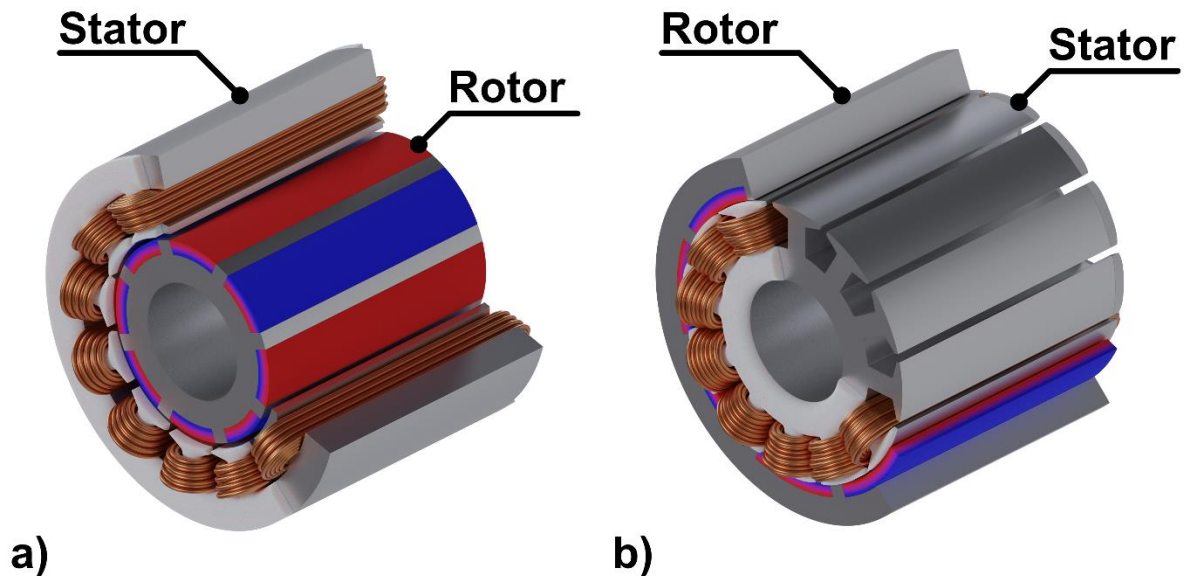


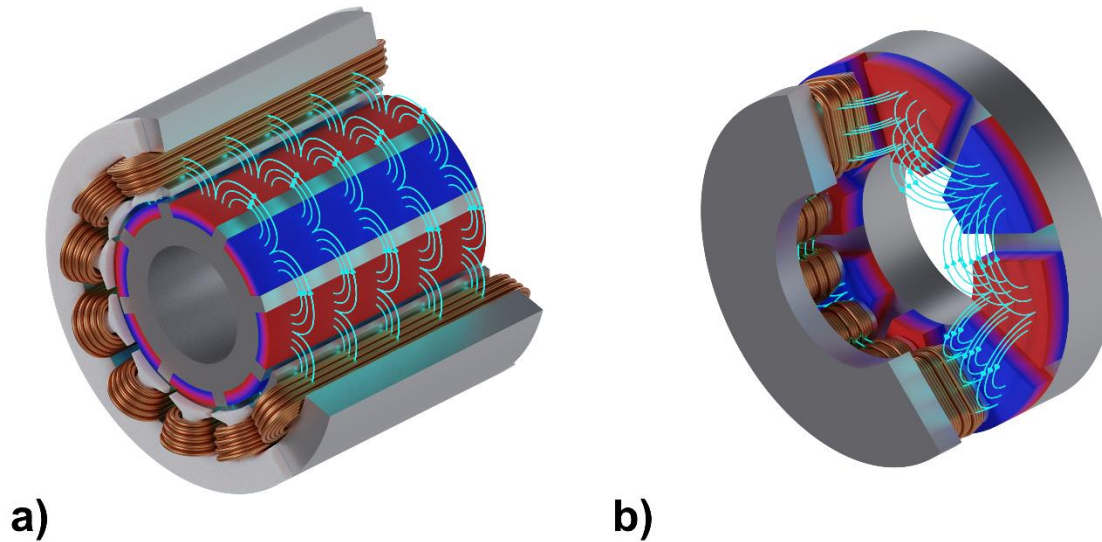
Figure 2.7: How the stator and rotor relate in an in-runner machine a) and an out-runner machine b) respectively, here illustrated using sectioned permanent magnet synchronous machines.

### 2.3.1. Permanent Magnet Synchronous Machine

In permanent magnet synchronous machines (PMSM), the rotor is outfitted with permanent magnets (PMs) and the stator incorporates armature windings. The current in the armature windings is controlled by an inverter in such a way that the magnetic field generated by the windings rotates synchronously with the magnetic field of the permanent magnets causing the rotor to rotate. One major benefit of permanent magnet synchronous machines is that they can generate torque at zero rotational speed. They also have a high torque density compared to other electric machines [8].

### 2.3.2. Magnetic Machine Topologies

Electric motors can be classified by their magnetic topology, i.e., in what directions the magnetic flux of the motor travels. The most common topologies are radial and axial (see Figure 2.8) though there are also hybrid machines that utilize aspects of both topologies.



*Figure 2.8: Flux topologies in a radial machine a) and an axial machine b) respectively. The cyan lines indicate the magnetic field, extending radially in a) and axially in b). The magnetic field lines are only illustrative and do not accurately represent reality.*

## 3. Method

### 3.1. Vehicle Simulations

Vehicle simulations are a commonly used tool in designing and optimizing vehicles. By performing simulations, expensive and time-consuming physical tests can be avoided, leading to shorter development times, and allowing for more time to optimize [9]. One such simulation software, that will be used in connection to this work, is “CarMaker” which is developed and maintained by “IPG Automotive” [10].

#### 3.1.1. Vehicle Model

The vehicle model used in CarMaker is very detailed and allows for a lot of customization, making it possible to model a wide range of four wheeled vehicles, including formula student vehicles. Formula student teams have access to a couple of different formula student vehicle models, which they can use as is, or use as a basis for modeling their own vehicles for simulation. All CarMaker vehicle models are in turn described by a series of system or component models with associated parameters. These models can be swapped out for other models to assemble the desired vehicle. For example, a vehicle can include one or more gearbox models. These can then be swapped out to model for example, either a manual transmission or an automatic transmission with their own respective parameters. All these parameters are also modifiable by the user to match the corresponding real parameters. Besides describing the functionality of a system or component the models also hold parameters describing physical aspects of the system or component. This includes the physical position of the object it represents, what part of the vehicle it is mounted to, the mass of the object, and the inertia of the object (where applicable). CarMaker also includes software to visualize the simulations as they are being carried out, allowing the user to get a feel for how the vehicle is behaving (see Figure 3.1).

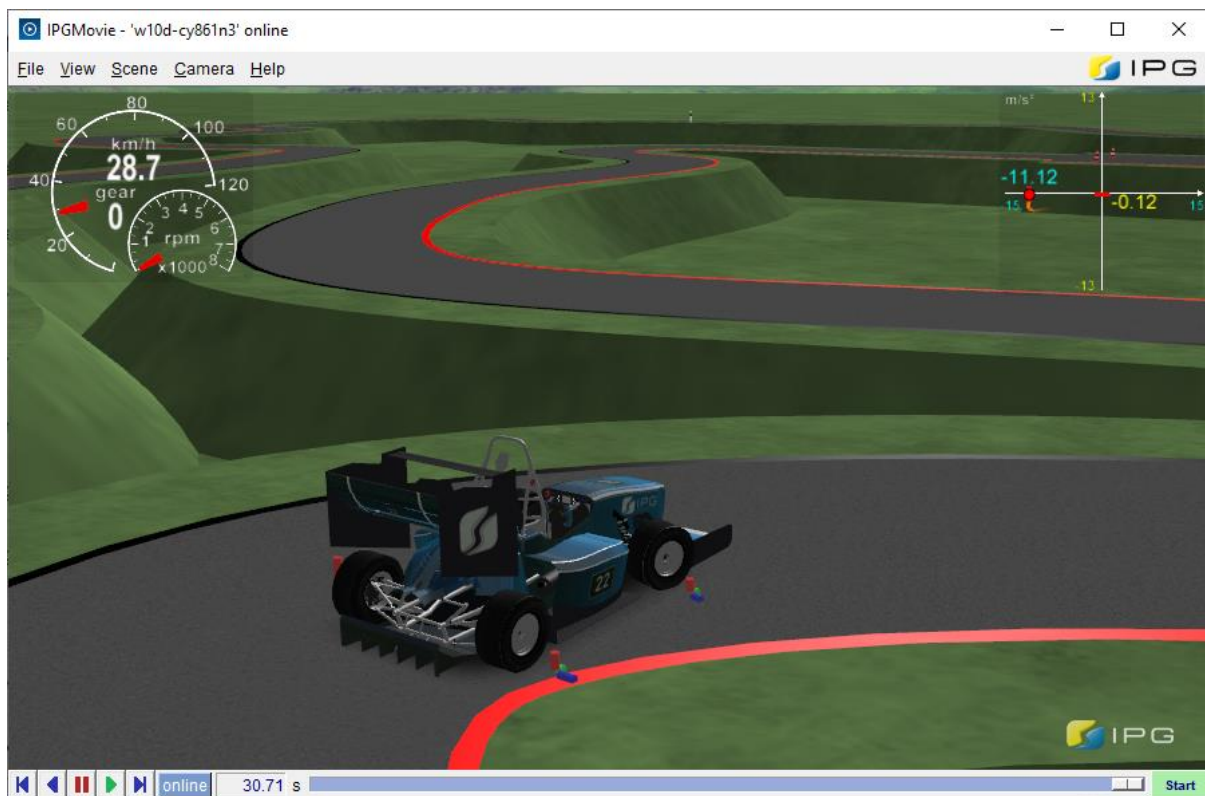


Figure 3.1: Screenshot of CarMaker showing the visualization tool during a simulation.

The user may also define their own models, such as their own type of transmission, though this is rather complicated and involves writing custom code. CarMaker also functions well in conjunction with other software, such as MATLAB and Simulink, which can be used to interject logic into the simulations. This is commonly used to design, test and optimize things like torque vectoring [11]. For a more detailed discussion of the functionality and capabilities of CarMaker the reader is referred to official documentation published by IPG Automotive such as the CarMaker User Guide and CarMaker Reference Manual.

As previously mentioned, CarMaker allows for a lot of customization and almost all aspects of the vehicle can be modified. The models and parameters that can be modified are divided into a set of categories such as: body, suspension, steering, tires, brake and powertrain (see Figure 3.2). For the simulations carried out as a part of this thesis one of the standard formula student vehicle models will be used and only models and parameters concerning the powertrain of the model will be modified.

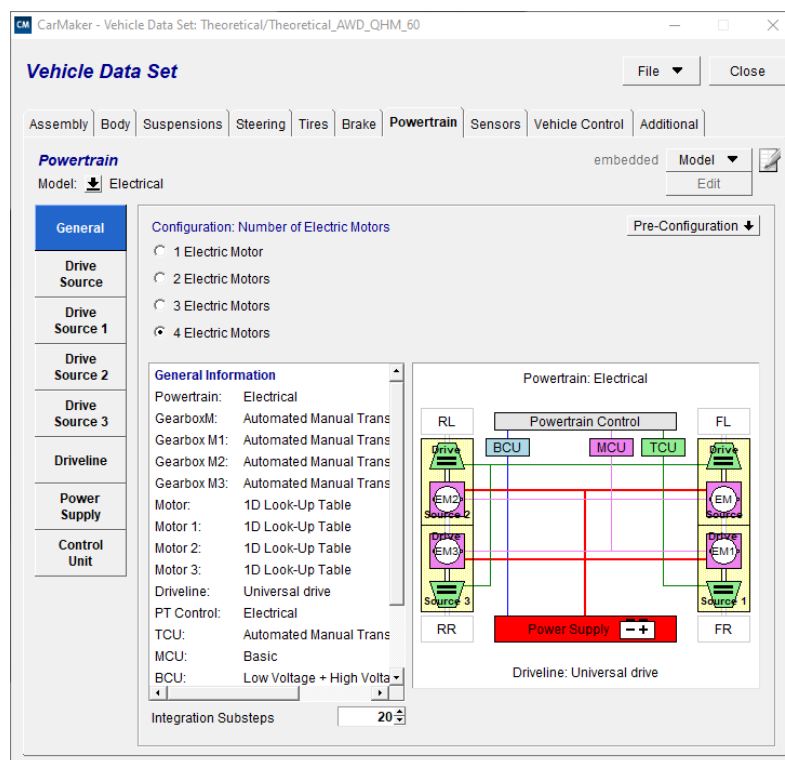


Figure 3.2: Screenshot of CarMaker user interface showing the window used for customizing vehicle system/component models and parameters.

### 3.1.2. Simulation Environment

Besides a detailed vehicle model, CarMaker also uses detailed environments for the simulations. These environments define where the vehicle should drive and can even include things like traffic signs, traffic lights, and other vehicles that the simulations will have to take into account and navigate around. These options are of no interest when modeling a formula student vehicle as they are not intended to operate under such conditions, but it does show the depth of possibility when it comes to these simulations. For simulating a formula student vehicle, a simple track which mimics a real track that a formula student vehicle might compete on is used (see Figure 3.3).

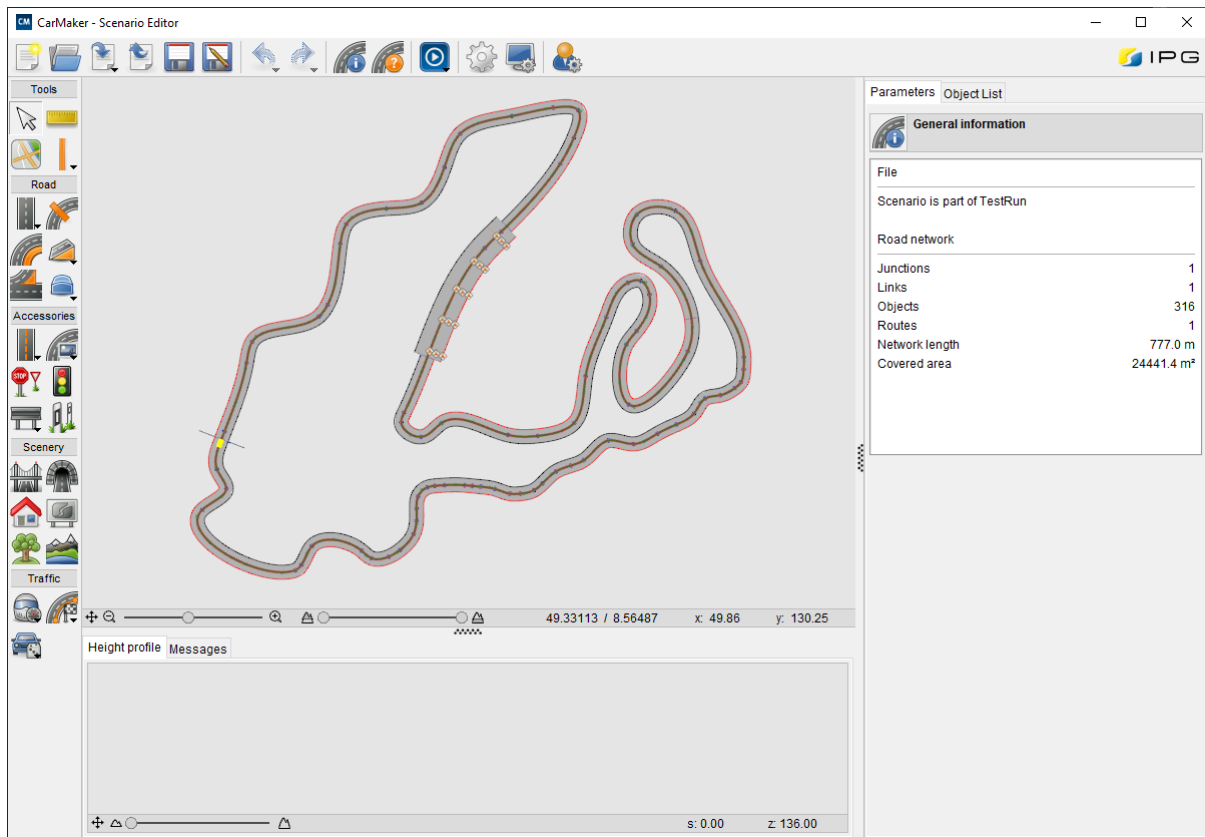


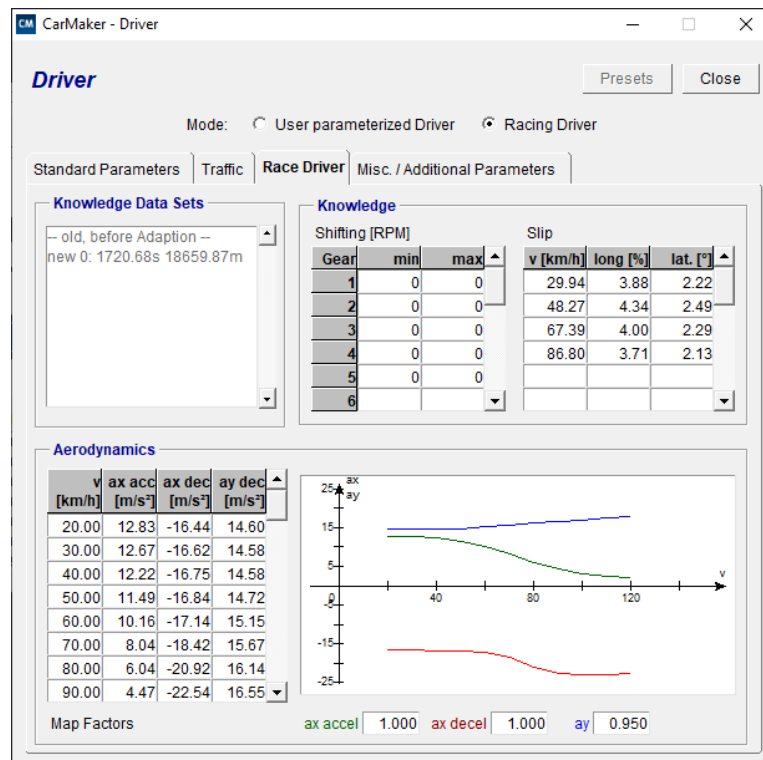
Figure 3.3: Screenshot of CarMaker user interface showing the Scenario Editor window and one of the tracks used for simulation.

### 3.1.3. Driver Model

The last part of the simulation is the driver model which actually controls the vehicle to perform the desired maneuvers to complete the objective of the simulation. A maneuver details the end conditions or a series of end conditions to be completed one after another to complete the simulation. This could for example be to accelerate as quickly as possible until the car has traveled a distance of 75 meters, mimicking the acceleration event at competition or it could be to complete one lap of the circuit, etc. CarMaker comes with two different types of driver models. One which is good for representing a typical driver under typical driving conditions



and one which is good for representing a racing driver in a competitive setting (see Figure



3.4).

Figure 3.4: Screenshot of CarMaker showing the driver configuration window after one round of driver adaptation.

For the simulations carried out as a part of this thesis the racing driver model was used. This model first requires training on the specific vehicle model which will be simulated. During the training the driver model learns the limits of the vehicle, which includes how fast it can accelerate and decelerate without losing grip, how quickly it can turn without losing grip at different speeds, and when to optimally change gears if applicable. After teaching the driver model the limits of the vehicle, the desired simulations can be carried out with the driver model trying to maximize the performance of the vehicle (driving at the limits of the vehicle).

### 3.1.4. Simulation Results

After a simulation has been carried out almost all parameters of the simulation can be inspected to see how they have changed over time or over distance traveled, etc. (see Figure 3.5) This can be used to identify weaknesses of the vehicle configuration and how changes to the configuration impact these parameters between different simulations. For this thesis, this tool was, amongst other things, used to identify performance requirements, both peak requirements and average requirements.



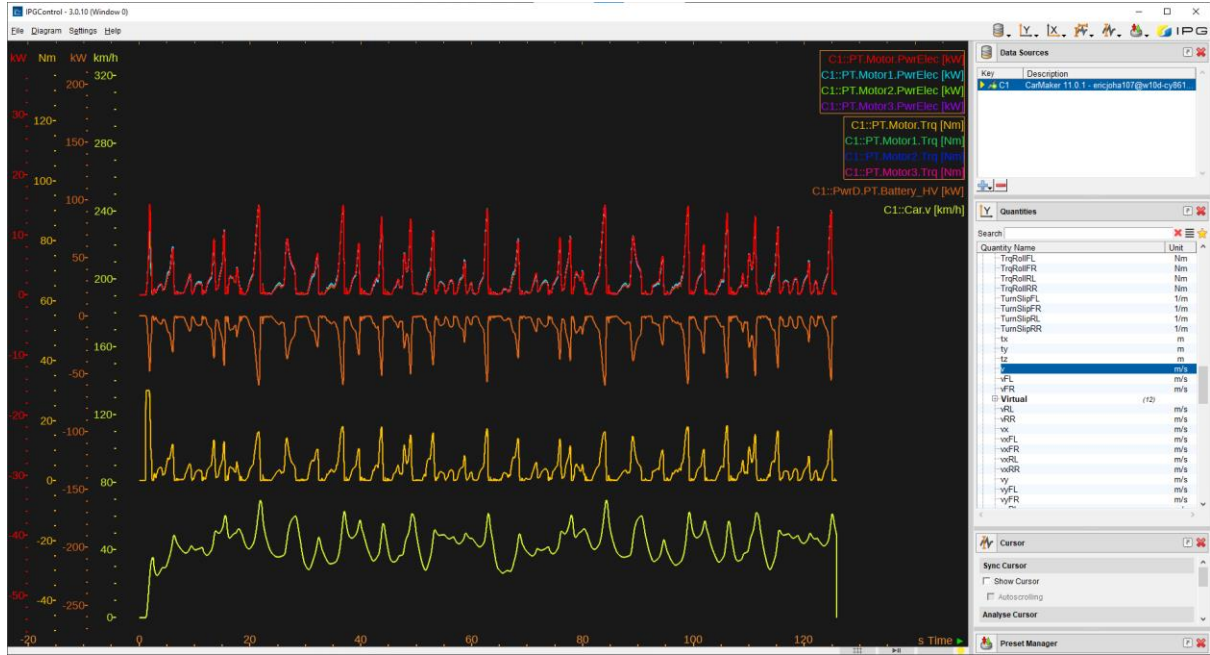


Figure 3.5: Screenshot of CarMaker showing the window used for analyzing simulation parameters.

## 3.2. Electric Machine Design Process

The design process for making electric machines often incorporates a fair bit of initial guess work followed by iterative improvements. One such design process is outlined in the book “Design of Rotating Electrical Machines” by Juha Pyrhönen [12], a modified version of which, more suitable for the design of a permanent magnet synchronous machine, will be presented and used in this text. This design process is exclusively analytical and is only intended as a starting point for more detailed analysis. Usually, machine design includes a great deal of finite element analysis for electro mechanics as well as structural mechanics and thermodynamics. An analytical approach like this should however be sufficient to get an estimation of the mass and inertia of a specific machine.

### 3.2.1. Performance Targets

Before starting the actual design work, the desired performance targets of the electric machine as well as some construction characteristics must be specified, this includes:

- < Machine geometry
- < Rated power,  $P$
- < Rated speed,  $n$
- < Rated voltage,  $U$
- < Number of poles,  $N_{poles}$
- < Number of slots,  $N_{slots}$
- < Number of phases,  $N_{phases}$

### 3.2.2. Primary Dimensions

With knowledge about the geometry and the performance targets of the machine the primary dimensions can then be calculated. The primary dimensions are:

- <  $D_r$  rotor diameter [m]
- <  $l'_r$  equivalent rotor length [m]

and can be determined by satisfying the following equation:

$$T_{max} = \sigma_{F,tangential} \times \frac{\pi D_r^2}{2} \times l'_r \quad (3.1)$$

where:

- ◁  $T_{max}$  is the maximum torque of the motor [Nm]
- ◁  $\sigma_{F,tangential}$  is the tangential stress experienced at the surface of the rotor [Pa]

Assuming sinusoidal flux density and current density in the air gap of an electrical machine, the tangential stress can be calculated using:

$$\sigma_{F,tangential} = \frac{A\hat{B}_\delta}{\sqrt{2}} \quad (3.2)$$

where:

- ◁  $A$  is RMS linear current density [kA/m]
- ◁  $\hat{B}_\delta$  is the peak air gap flux density [T]

For the initial phase of the electric machine design empirical values for linear current density and flux density can be used to estimate achievable tangential stresses which can be used to calculate what dimensions are needed to achieve a desired torque using equation (3.1).

### 3.2.3. Air Gap

After calculating the primary dimensions, the air gap of the machine should be decided. The length of the air gap has a significant impact on the performance of the electric machine and the optimal air gap length for a specific machine depends on several different parameters. Generally, a smaller air gap is usually better. This is certainly the case for high torque, low speed, PMSM machines. Reducing the air gap decreases the required PM thickness which saves mass and inertia. For high-speed machines, however, the air gap might need to be increased to avoid excessive energy losses. For permanent magnet synchronous machines with more than one pole pair, the air gap length can be calculated using the following equation:

$$\delta = \frac{0.18 + 0.006 \times P^{0.4}}{1000} \quad (3.3)$$

where:

- ◁  $P$  is the rated power [W]

### 3.2.4. Armature Winding

The number of coil-turns per phase is calculated using the following equation:

$$N_{turns,phase} = \frac{\sqrt{2}E_m}{\omega k_w \hat{\Phi}_m} \quad (3.4)$$

where:

- ◁  $E_m$  is the EMF (Electro Motive Force) [V]
- ◁  $\omega$  is the angular velocity [rad/s]
- ◁  $k_w$  is the winding factor [-]
- ◁  $\hat{\Phi}_m$  peak pole flux [Wb]

Peak pole flux can be calculated using the following equation:

$$\hat{\Phi}_m = l'_r \tau_p \alpha_i \hat{B}_\delta \quad (3.5)$$

where:

- <  $\tau_p$  is pole pitch [m]
- <  $\alpha_i$  is saturation factor [–]

The EMF can be estimated to be:

$$E_m \in [0.9U_s, 1.1U_s] \quad (3.6)$$

where:

- <  $U_s$  is terminal voltage [V]

Given the number of coil-turns per phase, the number of conductors per slot can be calculated using the following equation:

$$N_{c,slot} = \frac{2N_{||}N_{phases}}{N_{slots}}N_{turns,phase} \quad (3.7)$$

where:

- <  $N_{||}$  is the number of parallel paths [–]
- <  $N_{slots}$  is the number of slots in the stator [–]

### 3.2.5. Discretization

The equation used to calculate the number of conductors per slot in section 3.2.4 does typically not result in an integer number which of course is required in practice; thus, the number of conductors need to be discretized. This discretization also means that the estimated air gap flux density is no longer valid and a new one can be calculated using equation (3.4).

### 3.2.6. Geometry

Using the corrected flux density, the width of the stator teeth can be calculated using the following equation:

$$w_{st} = \frac{l'_r \tau_s \hat{B}_\delta}{k_{Fe} l'_s \hat{B}_{st}} + 0.001 \quad (3.8)$$

where:

- <  $\tau_s$  is slot pitch [m]
- <  $k_{Fe}$  is the iron space factor [–]
- <  $\hat{B}_{st}$  is the reference flux density allowed in the stator teeth [T]

The dimensions of the slots depend on the current, which can be calculated using the following equation:

$$I = \frac{P}{N_{phases} \eta U_s \cos \varphi} \quad (3.9)$$

where:

- <  $\eta$  is the efficiency of the motor [–]
- <  $\cos \varphi$  is the power factor [–]

Using the current, the cross-sectional surface area of a single conductor can be calculated using the following equation:

$$S_c = \frac{I}{N_{||}J} \quad (3.10)$$

where:

- ◁  $J$  is the permissible current density in the armature windings [ $A/m^2$ ]

Having determined the cross-sectional surface area of a single conductor the cross-sectional surface area of a single slot can be calculated using the following equation:

$$S_{slot} = \frac{N_{c,slot} S_c}{k_{Cu}} \quad (3.11)$$

where:

- ◁  $k_{Cu}$  is the copper space factor [-]

Once the total cross-sectional surface area for one slot is determined the exact geometry of the slots can be determined based on desired slot shape. The rotor and stator yokes can then be calculated using the following equations:

$$h_{sy} = \frac{\hat{\phi}_m}{2k_{Fe} l_s \hat{B}_{sy}} \quad (3.12)$$

$$h_{ry} = \frac{1.2 \times \hat{\phi}_m}{2k_{Fe} l_s \hat{B}_{ry}} \quad (3.13)$$

where:

- ◁  $\hat{B}_{sy}$  is the permissible flux density in the stator yoke [T]
- ◁  $\hat{B}_{ry}$  is the permissible flux density in the rotor yoke [T]

### 3.2.7. Magnet Height

The thickness of the permanent magnets can then be calculated using the following equation:

$$h_{PM} = \frac{\hat{U}_{m,\delta} + \hat{U}_{m,st} + \frac{\hat{U}_{m,sy}}{2} + \frac{\hat{U}_{m,ry}}{2}}{\frac{B_r - B_{PM}}{\mu_{PM}}} \quad (3.14)$$

where:

- ◁  $\hat{U}_{m,\delta}$  is the magnetic voltage in the air gap [A]
- ◁  $\hat{U}_{m,st}$  is the magnetic voltage in the stator teeth [A]
- ◁  $\hat{U}_{m,sy}$  is the magnetic voltage in the stator yoke [A]
- ◁  $\hat{U}_{m,ry}$  is the magnetic voltage in the rotor yoke [A]
- ◁  $B_r$  is the remanent flux density of the permanent magnets [T]
- ◁  $B_{PM}$  is the flux density in the permanent magnets at the loading point [T]
- ◁  $\mu_{PM}$  is the permeability of the permanent magnets [H/m]

## 4. Result

### 4.1. Vehicle Simulations

#### 4.1.1. Vehicle Configuration Comparison

As part of this work, several vehicle simulations were performed to compare different drivetrain configurations. All drivetrains were modelled with really high, constant, torque-speed curves. More torque than these vehicles could ever utilize. This was done to not unintentionally create any disparity in available torque between different configurations. This is a reasonable approach since the vehicles are still limited by the amount of torque they actually are able to utilize. Applying too much torque would just cause the vehicle to lose traction and the wheels to spin. The driver model used by the simulation always tries to use as much torque as possible without causing the wheels to spin (also staying on the track). It is also evident in the recorded data from these simulations that no configuration ever came close to utilizing all the torque that was available. This means that these simulations focus entirely on the mass of different configurations, how this mass is distributed, how much power the vehicles are allowed to utilize and where the torque generated can be applied.

In total, seven different vehicle configurations were simulated in two different scenarios. Three of these were 4WD configurations: one using four hub motors, one using dual hub motors in the front and dual in-board motors in the rear, and one using dual hub motors in the front and one motor in the rear connected to the wheels with a limited slip differential. There were also three RWD configurations: one using dual hub motors, one using dual hub motors, and one using one motor and limited slip differential. Lastly there was one FWD configuration using dual hub motors. All 2WD configurations were allowed to draw a maximum of 80 kW of power from the battery pack, whereas all 4WD configurations were limited to drawing a maximum of 60 kW of power from the battery pack. These are the limits specified in the FSUK rules for 2WD and 4WD electric vehicles [1]. Other competitions, such as FSG have the same 80 kW power limit regardless of driven wheels [2]. The FSUK rules are used as these are the most restrictive in this particular area. The two different simulated scenarios are: one lap (running start) around a short circuit, mimicking one lap of an endurance or auto-cross event, and one acceleration event in accordance with competition rules. The results of the vehicle simulations are presented in Table 4.1.

Table 4.1: The different drivetrain configurations that were compared, the total mass of the vehicle, the maximum allowed power draw from battery and how they performed during a lap and during an acceleration event.

#	Description	Total Mass	Power	Lap Time	Acceleration
1	Quad Hub Motors	226.26 kg	60 kW	63.795 s	5.323 s
2	Dual Hub Motors + Dual Inboard Motors	226.26 kg	60 kW	64.074 s	5.321 s
3	Dual Hub Motors + Limited Slip Differential	231.26 kg	60 kW	63.909 s	5.288 s
4	Dual Hub Motors (RWD)	216.26 kg	80 kW	65.643 s	5.733 s
5	Dual Inboard Motors (RWD)	216.26 kg	80 kW	65.604 s	5.746 s
6	Limited Slip Differential (RWD)	221.26 kg	80 kW	65.979 s	5.808 s
7	Dual Hub Motors (FWD)	216.26 kg	80 kW	72.321 s	7.027 s

The vehicle simulations make it very obvious that four-wheel drivetrain configurations are the most favorable. These results match when comparing the best performing formula student

vehicles at competitions [8]. Despite being heavier and not being allowed to utilize as much power as the two-wheel configurations, they still performed better over the course of a lap and in the acceleration event. This once again points to the biggest limiting factor of these vehicles being traction. There does however not seem to be a big difference between different configurations with the same driven wheels.

### 4.1.2. Vehicle Performance Requirements Simulations

Having determined that 4WD vehicle configurations are the most favorable, more vehicle simulations were performed to determine reasonable performance requirements for formula student vehicles. The decision was made to go forward with a quad hub motor configuration since this offers more practical benefits than the other two options. For one, a quad hub motor configuration would require only one design that can be easily reused for all wheels. In the case of dual hub motors in the front and a motor with a limited slip differential in the rear there would be a need to design two separate solutions. Even with the case of dual hub motors in the front and dual in-board motors in the rear, where the same motors could be used in the front and rear. There would still have to be two separately designed solutions out by the wheels in the front and rear. The hub motors also make space in the chassis for other components.

Thus, a quad hub motor configuration was simulated to determine the torque, power, and speed requirements for designing a competitive vehicle. The results of these simulations are presented in Table 4.2.

*Table 4.2: Performance requirements, measured at the wheels, for one wheel in a quad hub motor configuration.*

Parameter	Value
Rated Torque	150 Nm
Maximum Torque	300 Nm
Rated Speed	1000 RPM
Maximum Speed	1500 RPM
Rated Power	15 kW
Maximum Power	25 kW

## 4.2. Concepts & Ideas

This section will present the conceived ideas and concepts that potentially could be implemented to reach the goal of increasing the performance of a formula student vehicle.

### 4.2.1. Ideas

Here different ideas of potential improvements are presented. All ideas are assumed to be in relation to a vehicle with hub motors unless otherwise stated.

#### 4.2.1.1. Combined Stator and Upright

The most common configuration when using hub motors among formula student teams is to mount the motor and gearbox to an upright. This is the approach taken by Clear River Racing in all of their electric vehicles to date and is also common among other formula student teams using hub motors. By combining the upright and the stator of the electric machine into one component the total mass of the assembly could be decreased. This could also help with packaging as it could decrease the total length of the assembly. There are teams who have already implemented solutions similar to this by combining the stator and the cooling jacket of the motor.

#### **4.2.1.2. Combined Rotor and Rim**

If using an outrunner machine, the rotor could be designed to also act as the rim of the wheel, thus potentially decreasing the mass of the system by eliminating the need for a separate rim. This would however entail making the outer diameter of the electric machine rather large which could increase the inertia of the system by moving the mass of the motor further from the center of rotation. Having a large air gap diameter would however result in the electric machine producing a lot of torque, possibly circumventing the need for a gearbox which would decrease the total mass of the system. Also, not having a gearbox and already producing the required torque would mean that the electric machine would not have to rotate nearly as quickly as a smaller machine, meaning that the energy required to get the motor spinning at sufficient speeds may not increase, despite the increased inertia brought about by a larger diameter (see equation (2.2)). This does however come with some more practical downsides, like not being able to quickly change tires for example due to wear or weather conditions. Also, wanting to change tire models could require redesigning the electric machine or limiting the selection of tires. Not being able to quickly change tires according to weather conditions could be considered acceptable for the formula student application. There is no need to quickly change tires due to wear mid competition, like in for example: formula one competitions, as there are no pit stops allowed and generally there is no need to change the tires at all during competitions. The only time a team is required to change tires is if the weather conditions change to require wet tires instead of slicks. This is not timed but if changing tires takes far too long the team might not have time to compete in the dynamic events before the competition is over.

#### **4.2.1.3. Combined Gearbox and Hub**

By combining the function of the hub into the gearbox the need for a separate hub can be eliminated. This is quite a common solution amongst formula student teams which design their own gearboxes. The most common type of gearbox in this scenario is a planetary gearbox where the planet carrier also functions directly as the hub of the vehicle, with the wheel mounted directly to it. Not only does this eliminate the need for a hub, and the mass and inertia associated with it, it can also improve packaging, decreasing the length of the upright assembly.

#### **4.2.1.4. Air Cooling**

By designing an electric machine that can be entirely cooled by air flow, the need for a liquid cooling system could be eliminated, and consequently, all the mass associated with such a system can be eliminated. Using hub motors offers many ways in which air flow could be increased and/or directed to achieve better cooling of the machine. Though particular effort would also have to be made in the dimensioning and design of the machine for this to be possible, due to the true limiting factor of an electric machine, often time, is thermal in nature. One clear benefit that electric machines have in this scenario, compared to combustion engines, is that electric machines only produce heat when they are in motion as they have no idle state. In the case of traction applications this means that there will always be air flowing over the motors (assuming that they are not blocked in any way) as they are producing heat. There will also be spinning components which could be modified to also act as fans, increasing the air flow over the machine. One common such implementation is to design the rim of the wheel to pull air through the wheel, which in this case would make the air flow over the machine, cooling it in the process. This completely air-cooled approach could mean that the machine would have to be designed as a more massive machine to avoid thermal issues. It would be very difficult to design a machine that could be cooled as efficiently using air as a machine designed to be liquid cooled. Of course, a design like this does have some headroom in terms of weight, equal to the weight of the cooling system of a liquid cooled machine.

### 4.2.1.5. Integrated Mechanical Brakes

Most formula student vehicles use brake discs for their mechanical brakes. Which means they have a component which is only used for one thing, breaking. By using surfaces which are already required for other functions, as the friction surface, the need for a separate brake disc, and the mass and inertia associated with it, would be eliminated. One caveat with this could be the need for cooling the brakes, which, depending on implementation, might be impaired. It is also important to protect sensitive components, such as the internals of the electric machine, from potential brake dust emitted as the brake pads wear down.

## 4.2.2. Concepts

The following sections will outline the details of complete drivetrain concepts, that will be discussed and evaluated, including the concept used for the CRR23 car to act as a point of comparison.

### 4.2.2.1. CRR23

The drivetrain concept for the CRR23 vehicle entails dual hub motors, one on each rear wheel. One such assembly can be seen in Table 4.1Figure 4.1 and the properties of the entire drivetrain are presented in Table 4.3.

*Table 4.3: Full drivetrain properties for the CRR23 concept.*

Property	Value
Total peak torque	320 Nm
Total mass	27.028 kg
Total inertia	93 100 kgmm <sup>2</sup>
Total equivalent mass	27.121 kg
Torque density (mass)	11.840 Nm/kg
Torque density (inertia)	3.4355 Nmm/kgmm <sup>2</sup>
Torque density (equivalent mass)	11.799 Nm/kg



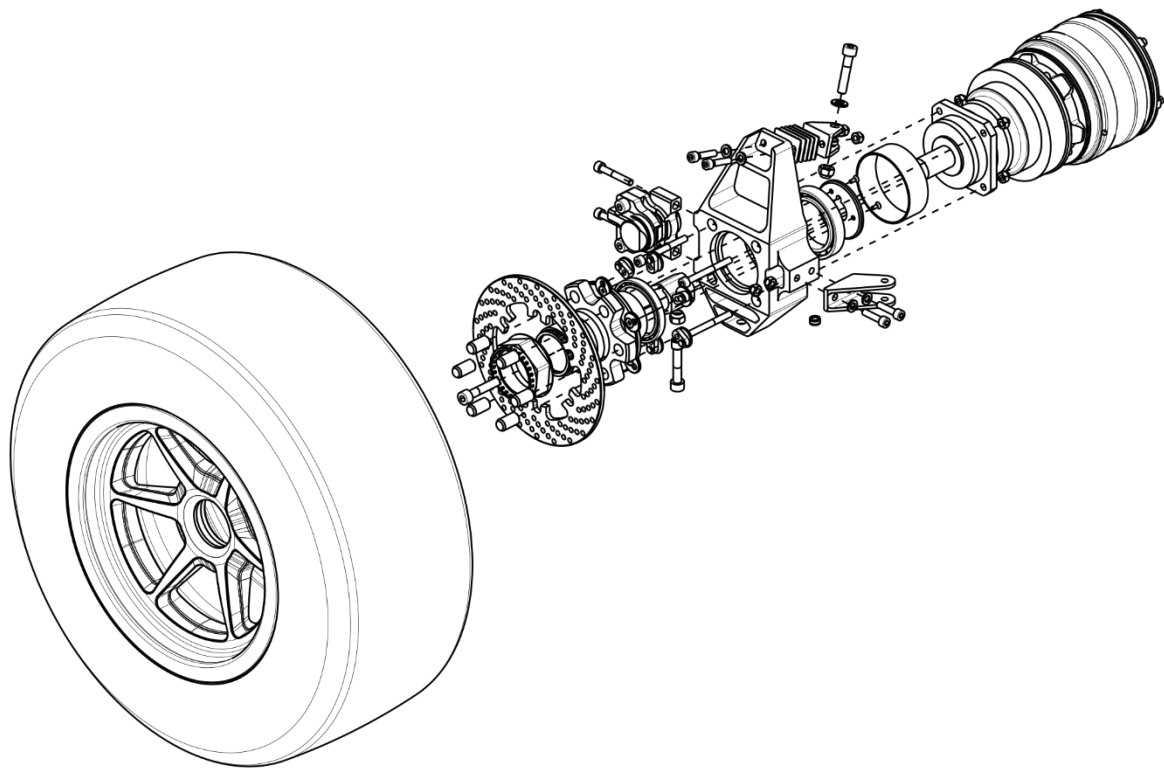


Figure 4.1: Rear drivetrain assembly CRR23.

#### 4.2.2.2. Hubless Outrunner Machine

One concept which would eliminate a lot of components, and thus hopefully decreasing the mass and inertia of the drivetrain, would be to use an outrunner machine, designed with a large outer diameter, for high torque and low speeds eliminating the need for gearing, with a hollow center, using the stator as the upright, and using the rotor as the rim for the wheel. This would eliminate the need for a separate hub, upright, gearbox and rim. This concept could be combined with a typical brake disc, except for the brake caliper being mounted from the inside instead of the outside (see Figure 4.2). Alternatively, the brake could be more greatly integrated into the machine design as discussed in section 4.2.1.5. The concept could potentially also be designed to be completely air cooled as discussed in section 4.2.1.4. The large diameter, and thus large potential surface area does increase the likelihood of a machine like this being able to be completely air cooled without having to compromise too much in terms of mass and inertia.

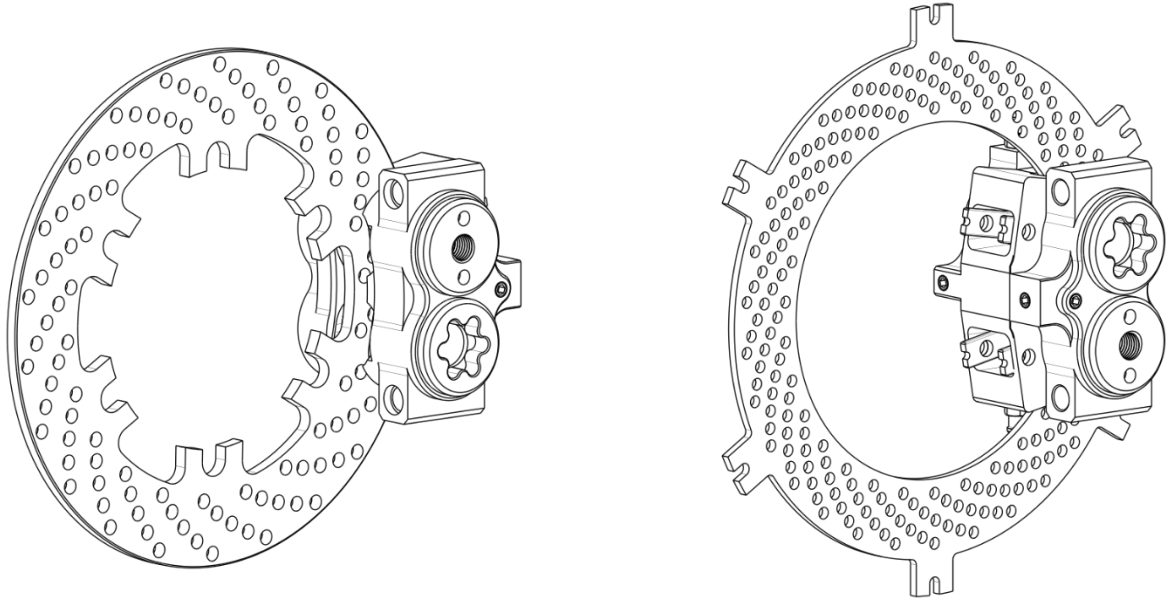


Figure 4.2: Brake caliper mounted externally (left) and internally (right).

#### 4.2.2.3. Hubless Rim Drive

Another concept which would eliminate a lot of components, but which does not rely on a large motor, or even a custom designed one necessarily, would be to go with a hubless design where the upright is circular, and the rim of the wheel takes the role of the hub. By adding a gear ring to the rim which is driven by a gear on the output shaft of the electric machine, there would be no need for a separate gearbox, saving mass and inertia. This would mean that the electric machine no longer is coaxial with the wheel. This could help lower the center of mass of the vehicle, which can improve handling and decrease the risk of tipping over. For front wheels, if the motor is offset a great distance from the turning axis of rotation, this would increase the turning inertia and thus the driver would have to exert more force when turning. This could be mitigated by offsetting the machine just up or down (down being preferred for lowering the center of mass, as discussed earlier). This is however where the attachment points for the control arms need to be located, possibly making it difficult to place them there as they would be competing for space.

### 4.3. Machine Design

Following the design process outlined in section 3.2, a machine compatible with the hubless outrunner machine concept discussed in section 4.2.2.2, and in accordance with the requirements specified in section 4.1.2, was designed. Since this concept does not include any gearing, the requirements for the electrical machine exactly match the requirements specified in Table 4.2.

The machine type was set to an out-runner, radial flux, PMSM. For the initial design of the number of poles was set to  $N_{poles} = 20$ . the number of slots was set to  $N_{poles} = 30$ , and the number of phases was set to  $N_{phases} = 3$ . The voltage was also set to  $U = 600\text{ V}$ , which is the highest permissible voltage according to competition rules [1] [2]. A high voltage tractive system has the benefit of allowing for thinner wires which saves weight and space [13]. The linear current density was assumed to be  $A = 50\text{ kA/m}$ , the armature winding current density was assumed to be  $J = 5.5\text{ A/mm}^2$ , the peak air gap flux density was assumed to be  $\hat{B}_\delta = 0.95\text{ T}$  and the maximum permissible flux densities of the stator yoke, rotor yoke, and stator

teeth was assumed to be  $\hat{B}_{sy} = 1.25 T$ ,  $\hat{B}_{ry} = 1.25 T$  and  $\hat{B}_{st} = 1.8 T$ , respectively. These values were based on empirically determined values tabulated in [12]. Based on the internal diameter of the intended tire, an air gap diameter of  $D_r = 230 \text{ mm}$  was set. Using equation (3.1) the rotor equivalent length was varied until a torque, matching the specified maximum torque, was reached. This resulted in  $l'_r = 110 \text{ mm}$ . The power factor was assumed to be  $\cos(\varphi) = 1.0$ , the efficiency was assumed to be  $\eta = 0.95$ , the saturation factor was assumed to be  $\alpha_i = 0.9$ , the winding factor was assumed to be  $k_w = 0.95$ , and the iron and copper space factors were assumed to be  $k_{Fe} = 0.97$  and  $k_{Cu} = 0.4$  respectively. This resulted in the final machine dimensions presented in Table 4.4.

Table 4.4: Final machine dimensions.

Parameter	Value
Air Gap, $\delta$	0.46 mm
Stator Diameter, $D_s$	230 mm
Rotor Diameter, $D_r$	230.92 mm
Rotor Core Length, $l_r$	109.08 mm
Stator Core Length, $l_s$	108.16 mm
Stator Tooth Width, $w_{st}$	13.4 mm
Stator Yoke Height, $h_{sy}$	9.16 mm
Rotor Yoke Height, $h_{ry}$	10.53 mm
Permanent Magnet Height, $h_{PM}$	1.24 mm

These dimensions were used to create a CAD-model (Computer Aided Design) of the electric machine (see Figure 4.3). This model was then used to calculate the mass and inertia of the machine, the results of which are presented in Table 4.5.

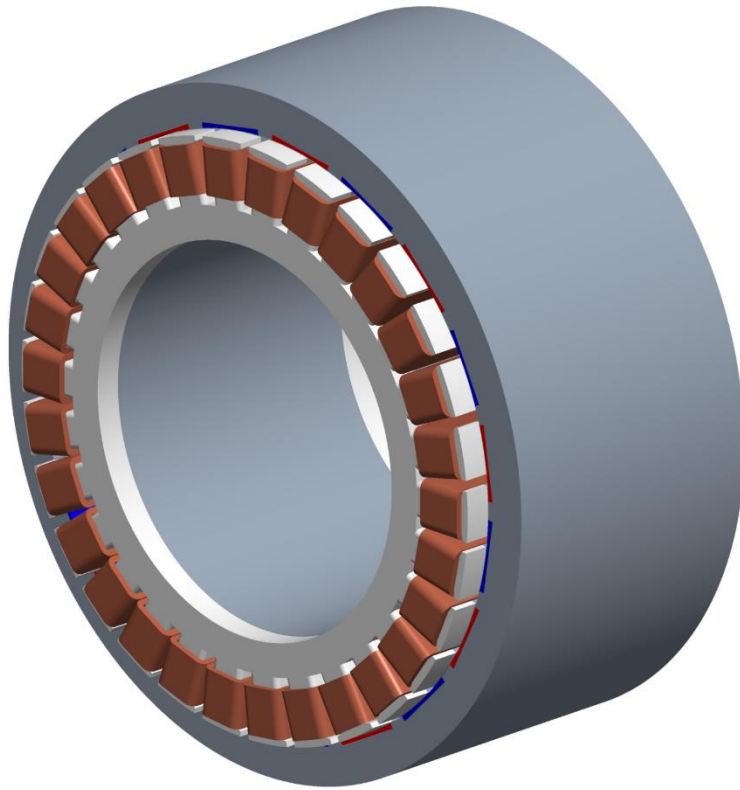
Table 4.5: Physical properties of machine designed for hubless outrunner concept.

Property	Value
Mass, $m$	26.4 kg
Inertia, $I$	146000 kgmm <sup>2</sup>
Equivalent mass, $m_e$	26.6 kg

A complete drivetrain utilizing four of these concepts, one for each wheel, would then have the total mass, inertia, equivalent mass and torque densities presented in Table 4.6.

Table 4.6: Full drivetrain properties for vehicles using four instances of the hubless outrunner concept.

Property	Value
Total peak torque	1200 Nm
Total mass	105.8 kg
Total inertia	586 000 kgmm <sup>2</sup>
Total equivalent mass	106.4 kg
Torque density (mass)	11.337 Nm/kg
Torque density (inertia)	2.0494 Nmm/kgmm <sup>2</sup>
Torque density (equivalent mass)	11.275 Nm/kg



*Figure 4.3: CAD model of electric machine designed for hubless outrunner concept, including stator, rotor, magnets, windings and protective end caps.*

## 5. Discussion

Part of this work has been focused on the design of electrical machines; this has been done using analytical methods, which is far from ideal. Though machine design often starts with analytical methods and empirical data for initial sizing, to achieve any reliable results, FEA (finite element analysis) is required, especially when trying to design high performance machines. The analytical methods used in this text are largely based on assumptions and/or empirical data.

When using analytical methods assumptions and simplifications are to be expected. When it comes to electrical machine design the biggest assumptions and simplifications are regarding the flux density field inside the machine. Many of the equations used here assume a sinusoidal air gap flux density which may be far from reality. FEA is a great tool to analyze the flux density field and to get a better estimation of the performance of the machine than just analytical methods can. These analytical methods also do not take specific material properties into account as they are based on empirical data from average properties.

The empirical data used from [12] takes into account a wide range of different machines and are intended to be as broadly applicable as possible. When designing high performance machines these values may not be all that representative. When designing high performance machines, the budget is usually a lot higher than for the average case. This allows for the use of permanent magnets with higher remnant flux densities and core materials capable of withstanding high flux densities. These more exclusive materials would allow for the machine to be significantly lighter whilst maintaining the same performance.

It should also be noted that a machine like the one suggested in the hubless outrunner concept is very unusual, machines are seldom made to be “hollow” which may negatively impact the relevance of the used design process on this particular type of machine. There are however examples of “hollow” motors. Like the rim driven azimuth thrusters made by Kongsberg Maritime [14]. Which is an in-runner and not an out-runner like the concept, but it is an example of a “hollow” machine.

## 6. Conclusions

The vehicle configuration simulations showed quite clearly that 4WD configurations are to be preferred. Though all 4WD configurations had similar performance, quad hub motor configurations probably offer the most practical solutions.

Based on the data presented in this text it has to be concluded that the hubless outrunner concept is not a good solution as it performs slightly worse than the existing concept. It is possible that with more detailed analysis and by refining the design using dedicated tools, such as FEA, the mass and inertia of the concept could be decreased. The mass and inertia would however have to decrease quite considerably for the concept to be viable.

## 7. Future Work

The design of the machine described in the hubless outrunner concept should be elaborated, optimized and evaluated before the concept should be truly dismissed. It would also be interesting to research the possibility of using other machine types to realize the hubless outrunner concept. It would be especially interesting to investigate the possibility of using an axial flux machine instead of a radial flux machine. After designing the actual electric machine, the rest of the concept needs to be modelled.

Due to time constraints, the hubless rim drive concept was never evaluated so this remains to be done.

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