UNIVERSITY OF EXETER

I2 Individual Report

Virtual Wind Tunnel

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ECMM102

4th Year MEng Group Project

I certify that all material in this thesis that is not my own work has been identified and that no material has been included for which a degree has previously been conferred on me.

Signed………………………………………………………………...

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ECMM102

Virtual Wind Tunnel

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Abstract

Wind tunnels are used to study the flow of air around an object. The automotive industry uses wind tunnels to minimise drag in new designs. If a vehicle has low drag it can be more efficient, faster and quieter. These characteristics make the product better and add value to the business. By developing a virtual alternative, vehicles could be further improved by cutting ecological and financial costs and by virtue of being able to test multiple designs in quick succession, and implementing iterative improvement. This project aims to develop such a virtual wind tunnel by means of comparison with a physical wind tunnel, and design a concept car that can demonstrate the comparability. Finally, the concept car will be rendered and animated.

This report focuses on the design aspects of the project; specifically, the iterative design of the concept car, the manufacturing process, and the rendering process.

Keywords

Wind tunnel, CAD, ALM, Ahmed body, Automotive Design, Blender, Python

Contents

1.0 Introduction

This report goes through the individual progress for the Virtual Wind Tunnel fourth-year project. It begins by describing the background of wind tunnels, previous work, and the scope of this project with regards to individual aims and objects. It then moves on to methodology and results. The applications and implications of these findings are discussed, along with opportunities for future work, and improvements if the project were to be repeated. The report closes with an overview of project management and some conclusions, and discusses the project management and issues around sustainability.

There was a high level of cohesion within the group, so this report will habitually refer to reports by its members: Blades [1], Bolt [2], Browne [3], Docherty [4], Nima [5], Hamilton [6], and Walton [7].

2.0 Background

Wind tunnels emerged from work on aviation theory in the wake of the Industrial Revolution in the 19th Century. Specifically, they were designed to study drag, turbulence and viscous effects of air passing a solid body [8]. Other areas of engineering and science were quick to see the value of wind tunnels, and they have been deployed in the development of everything from skyscrapers to cars. Typically they consist of a closed volume through which a smooth airflow is driven over an object of interest. This approximates the fluid interaction of the object moving through air. Often the model is scaled down for practical and economic reasons. The analysis of the aerodynamic qualities of a design allows engineers to improve the performance of a product. Since inception, automotive manufacturers have used wind tunnels to develop faster, quieter and more efficient vehicles.

Despite these benefits, wind tunnels incur criticism for being expensive, difficult to analyse, and unrepresentative of real-life scenarios. Developing a computational alternative would cut costs, allow for iterative design, and improve researchers' ability to record, repeat and analyse a product's performance. Furthermore, an accurate virtual model can be rendered for display purposes.

The above reasons provide a commercial mandate for this project, which is to develop a computational alternative to the wind tunnel: a Virtual Wind Tunnel (VWT). The project is divided into three subgroups. The experimental group will focus on rebuilding a physical wind tunnel for validation, and testing the concept car using pitot tubes and hotwire anemometry. The high performance computing (HPC) group will develop a virtual wind tunnel using computational fluid dynamics (CFD) software Fluent [9], Pointwise [10] and OpenFOAM [11], and compare flow profiles and drag coefficients with the experimental group. The design group will implement an iterative process to design a four-seater concept car, manufacture the model, facilitate the integration of the model with the other two groups, and render the model with field data using Blender [12]. This report focuses on the design group; specifically, aspects around the iterative design process and the rendering.

2.1 Individual Objectives

Working within the design group, there are three individual objectives: to design the concept car iteratively using CAD and feedback from CFD optimisation tests; to manufacture the final concept car and facilitate with its integration into the other groups; and to take the concept car and combine it with field data to create still and animated renderings.

2.2 Individual Deliverables

The aforementioned objectives translate into three specific deliverables.

1. A final design for a concept car, optimised based on iteratively investigating the aerodynamic effect of design parameters.

2. A scaled physical model of the concept car.

3. A series of accurate, detailed rendered images of the concept car, and a script to automate and create others.

2.3 Review of Automotive Design

2.31 Ahmed Body

A 1984 study by the Society of Automotive Engineers developed a simple geometry to model car air flow [13]. Ahmed (et al) observed that almost 85% of vehicle drag was from pressure variations generated from the rear of the vehicle, which left a volume of low pressure in its wake as it moved forward. Most vehicle rears are can be approximated as a slanted plane, so the Ahmed Body was developed as a rectangular block with a slanted back (typically 20° – 35° [13]) and a bluff front. Figure 1 shows a typical example, and illustrates the high degree of turbulence behind the body.

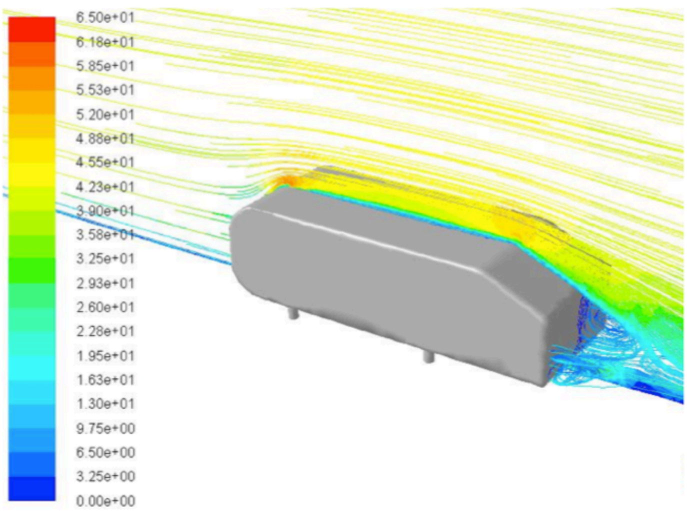


Figure 1. An image of an Ahmed body with a sloped rear of 30°, and coloured velocity pathlines

2.32 Automotive Development

In the contemporary automotive industry, design work starts by defining constraints and the minimum criteria of the vehicle [14]. The constraints are derived from regulation, cost pressures, and market demand; for example, a company could decide to produce a new 4x4 vehicle because customers want to exhibit their lifestyle aspirations. Typically, the next stage is to draw sketches – aesthetics are important for a successful product [14].

The next stage is where this project focuses. The sketches are materialised into clay models (typically at 1:4 or 1:2 scale) for wind tunnel testing [14]. The creation of these models can take days, deploys expensive labour, and can be difficult to move, while any non-minor optimisations require a full rebuild. The vehicle is attached to instruments such as pitot tubes and anemometers to measure the drag, turbulence, and forces generated by airflow. Additionally, the airflow may have smoke-like substances injected to create flow lines, which can be measured to imply turbulence and drag [8]. While approximately accurate, the method is not versatile; that is, it is difficult to record all data from one experiment. These drawbacks have led manufacturers to explore testing and optimisation in a virtual environment.

In this context, optimisation means to reduce the drag while retaining the desired physical features. On simple shapes, including individual components within cars (such as crankshafts), there are physics-based solvers (such as Solidworks Simulation [15]) that automate the optimisation process by testing variations of a base design within variable parameters to find the iteration with the best mechanical properties, within specified constraints. No such optimisation package is available for an entire car; so optimisation is done through knowledge of basic fluid dynamics, flow results from the virtual and physical wind tunnels, and automated optimisation upon individual components [14].

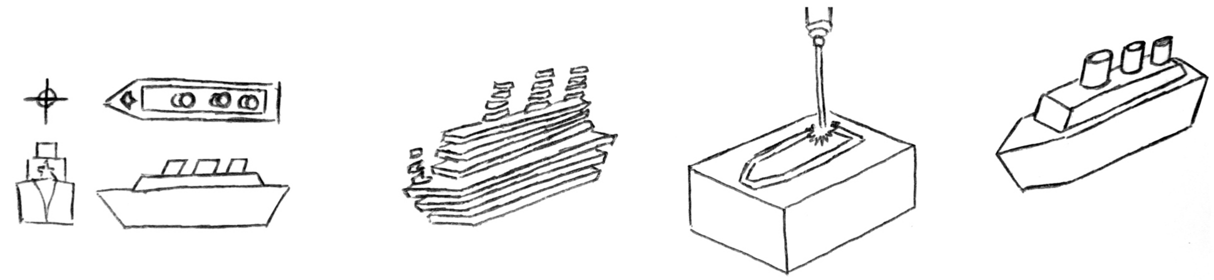
2.4 Review of Manufacture

The specifics of model construction differ from company to company, but most are handmade from a wire frame model layered with clay [14]. While craftsmanship allows for a high level of quality, and for the architect to spot inaccuracies during construction, it is slow, expensive and imperfectly precise.

Recent manufacturing developments have enabled new methods of construction. 3D printing in the form of Additive Layer Manufacturing (ALM) is rapid, inexpensive, efficient and precise, particularly with respect to small parts [16]. The model is derived from the surface geometry from a computer aided design (CAD) model, typically as a Stereo Lithography (STL) file, and deconstructed into multiple cross-sectional layers (around 100μm each), which are “stacked” into a physical model [16].

Some methods, like Fused Deposition Modelling (FDM), operate on the basis that polymer filament is melted, extruded from a nozzle and deposited onto the lower layer, bonding as it cools. For overhand and free-standing geometry, this requires support structures [16].

One major method involves laser sintering. The laser is directed onto a container of polymer powder, which melts locally, creating a three-dimensional structure [16] as illustrated in Figure 2. For greater accuracy, the model can be made up to 1mm larger than necessary, and then fine-tuned and smoothed using a slower subtractive process. The process is well positioned to become important in wind tunnel testing, since the models are accurate, repeatable and precise [16].



1. A virtual model of the desired shape is built in a CAD package and exported into a format readable by the ALM machine, typically .STL

2. The ALM software deconstructs the model into multiple thin layers, typically less than 100μm each

3. A laser is used to melt each layer onto a block of powder (in some cases liquid or sheet). At the end of the process the remaining powder is removed

4. On removal of the powder, the layers have been fused on top of each other to create a physical replica of the CAD model in step 1

Figure 2. The four stages of laser sintering ALM

ALM is not currently cheap enough for mass production, though some large automotive manufacturers have made full-scale concept cars using the process [17].

Another method of manufacture is Computer Numerical Control machining (CNC), which is superficially similar to ALM but differs fundamentally in method. Models are also defined from CAD data, but the CNC machine interprets as a series of commands (not a stack of layers) that will render a simple block of material into the desired geometry; most machines utilise a combination of techniques such as drilling or sawing [18]. Though cheaper and faster than ALM, it is less accurate and can result in rough or badly finished products. However, it is useful for basic prototyping or creating a large number of models [18].

2.5 Review of Rendering

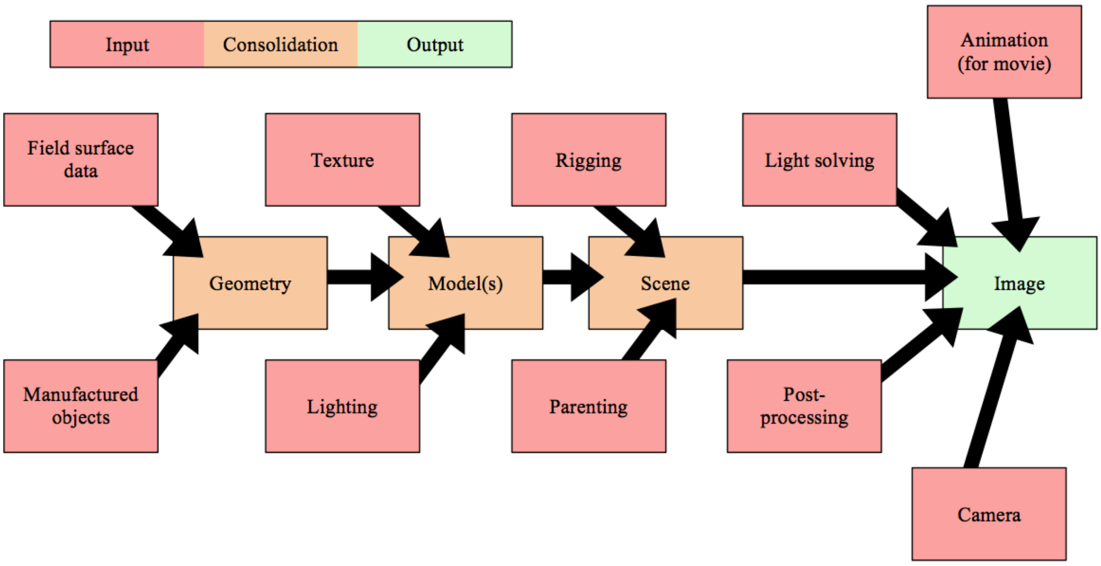


Figure 3. The process flow chart for rendering using Blender

Rendering, in the sense relevant to this report (computer graphics), refers to a process by which a model is converted into an image [19]. Figure 3 provides an overview of the process flow. Generally, the model will be three-dimensional and the image two-dimensional [19]. The model data typically comes from the same CAD model used for 3D printing. The rendering programme integrates the geometry, lighting, texture, perspective, mechanisation, shading, and camera sensor with respect to light physics, and outputs a digital image [19]. Generating a series of different, consecutive images can create animation.

Any graphical user interface (GUI) within a CAD programme could technically be considered rendering, since it is a visual representation of three-dimensional data points. Additionally, most CAD packages (Ansys, Solidworks, etc) include rendering functions that apply lighting and textures and export an image file [20].

The quality of these renders is limited, partly because of the lack of variables, but fundamentally because they work on a *surface* basis, not a *path-tracing* one [19]. A surface-based solver takes each vertex of an element and analyses it to find the effects of lighting and shading, then averages these to find the light properties of the surface as a whole [19]. A path-tracing solver tracks the light of each camera pixel backwards from the camera to any surface, and follows the diffracted light particles to their original sources. Because path tracing is unbiased and physically based, the result is a more faithful-to-reality image [19].

Path-tracing requires significantly more computing power than a surface-based approach (around 17x as much, as discussed in section 3.3), and is typically only found in dedicated rendering programmes. These programmes also provide a far greater degree of control over variables such as occlusion, subsurface scattering, specular reflection, translucency and sampling rates, to name but a few [21].

Blender is a good example of such a programme. Developed in the Netherlands and launched in 1995, it is freely available [12] under the GNU General Public License, and has been used in numerous feature films [21]. It renders three-dimensional models into images, videos or interactive game environments. Geometries can be constructed within the program or imported from an STL file. The geometry is typically a polygon mesh, but Blender can also work with Non-Uniform Rational B-Spline (NURBS) surfaces, Bezier curves (a technique that uses start, end, and attractive points to make curves that are infinitely enlargeable), B-meshes (Blender's own polygon mesh) and metaballs [21], as explained schematically in Figure 4. By default, Blender uses the aforementioned path-tracing light solver, but can be programmed to work on a surface-basis for faster results (as is necessary for real time rendering, such as in video games).

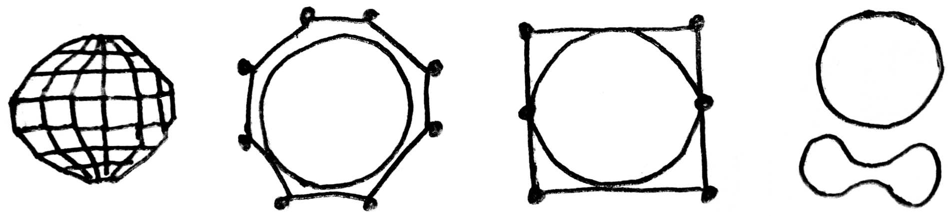


Figure 4. A two-dimensional polygon mesh, NURBS circle, Bezier curve circle, and metaball (L-R)

3.0 Methodology

3.1 Car design

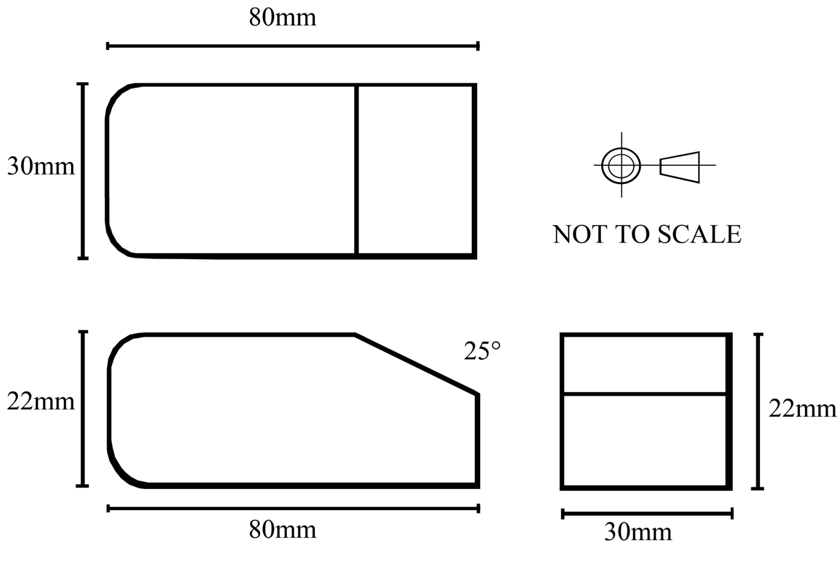


Figure 5. The Ahmed Body

The design of the concept car began by using Ahmed's body [13] as starting point due to the amount of data freely available, which was useful for the development of the VWT [6] (see figure 5). Using information from the experimental subgroup [4], the Ahmed body was defined to fit within a rectangular volume of length 375mm with a

300mm x 300mm cross-section. The body was constructed in Solidworks with a rear slant of 25°, a length of 80mm, a width of 30mm, and a height of 22mm. This is within the maximum cross-sectional area (5% of total) that allows the drag and pressure difference effects to develop into a representative flow profile.

While any car design could be used to verify the virtual wind, consideration is needed to prevent the geometry of the vehicle causing adverse effects. For instance, an unusual or complicated geometry (like a convertible) could be beyond the capabilities of OpenFOAM to solve correctly [22], or could take an impractically long time. Manufacturing capabilities are also limited by the budget (see section 7.3), reducing the possible complexity of the design. Table 1 evaluates the merits of six types of concept cars, while Figure 6 illustrates the six types.

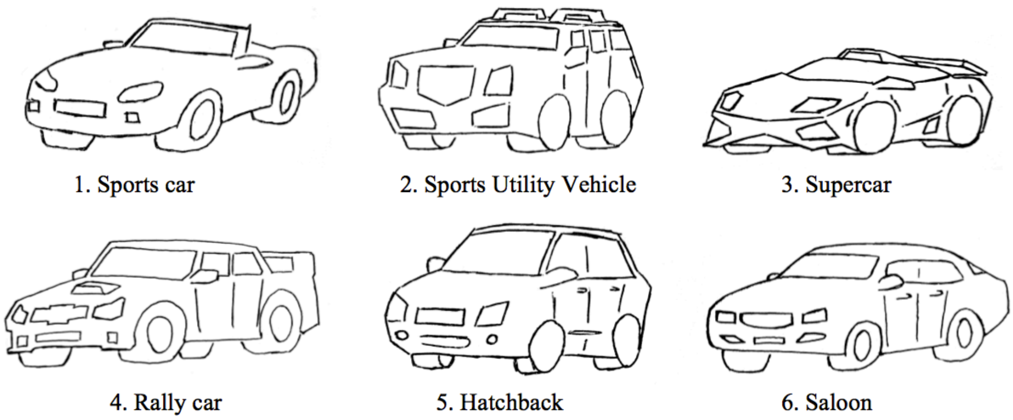


Figure 6. The six possible concept car types

	Scope for improvement	Ease/cost of ALM	Represent-ative	Mesh difficulties	Commercial application	Total
Weight	3	2	2	2	1	
Sports car	3	4	4	5	4	**39**
SUV	5	3	3	3	4	**37**
Supercar	2	3	2	2	3	**23**
Rally car	3	4	4	3	3	**34**
Hatch-back	3	5	4	4	5	**40**
Saloon	5	4	4	5	4	**45**

Table 1. Weighted matrix analysis of the six concept car designs

The matrix concludes that the best design is the saloon car, due to its improvable aerodynamics, simple shape (for mesh simplicity and comparability with a full-size car) and large share of vehicle sales. This decision introduces a constraints; the car must have four seats. Constraints are also implied by the 5% cross-sectional area maximum – combined with two rows of seats and crumple zones, and EU legislation for the definition of a car [23], this puts the maximum vehicle height around 1.5m, width 2.3m and length 4.0m.

Upon choosing the saloon design, an optimisation exercise was performed to determine the optimum criteria for aerodynamic efficiency. The Ahmed body was altered to approximate a saloon body (shown in figure 7), and three criteria were varied in Ansys Fluent: front windscreen angle, rear section angle, and fillet radius; the drag forces were found for each variation. Figure 8 shows the results.

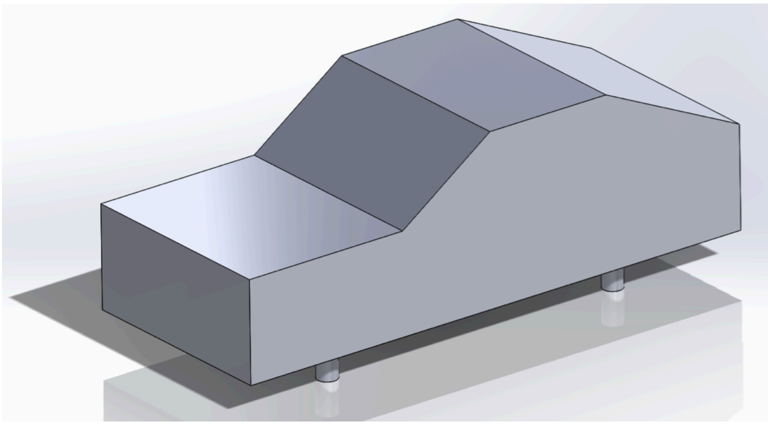


Figure 7. The modified Ahmed body used for parameter testing

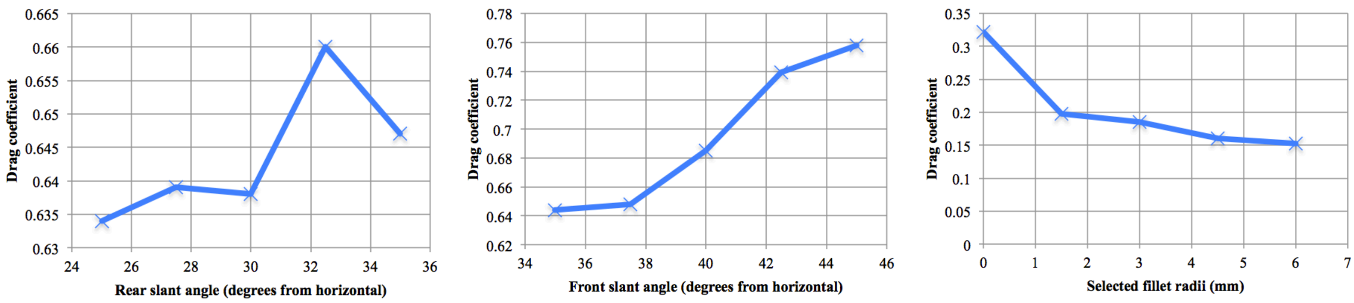


Figure 8. The effect of rear slant angle [3], front windscreen angle, and filleting radius [5] (L-R) on overall drag

The ostensive conclusions should be taken with some qualifications. By increasing the front angle while maintaining vehicle height, the length of the bonnet was altered; this could have its own effect on drag (by preventing the boundary layer from developing, for instance). Similarly, by increasing the rear angle the top of the car would become longer or shorter. But such is the difficulty of automotive design; most parameters are linked, and CFD analysis can only tell you about the vehicle as a whole [22]. Nevertheless, it is clear that to make the car as aerodynamic as possible it should be have low angled front and rear slants, with high fillet radii.

The final constraint was subjective; the car had to appeal aesthetically. This was accounted for by collective opinion gathering, and by working off eminently popular designs such as in [24].

Working within these constraints, the main body was formed in Solidworks by applying the lofting feature to several cross sections. Wing mirrors, wheel arches and a diffuser were added to the body. Development is illustrated in figure 9.

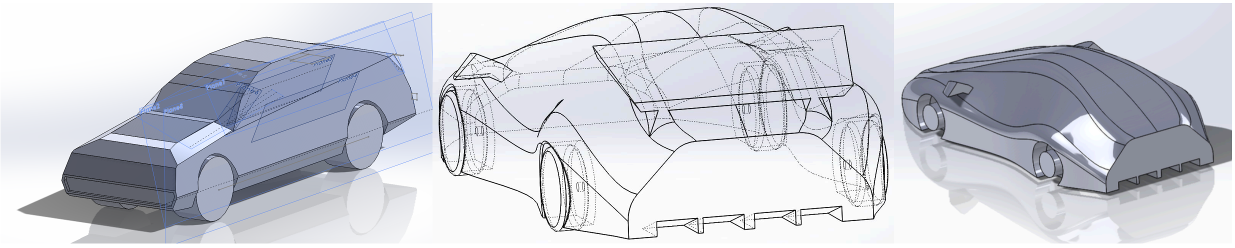


Figure 9. Early developments and the final concept car in Solidworks

3.2 Manufacture

On completion of the car design, the best manufacturing technique had to be chosen. Three techniques are available in the University's Centre for Additive Layer Manufacturing (CALM) [25]. A weighted matrix study was undertaken to find the most appropriate, as shown in table 2.

Process	Surface finish (/5)	Manufacture time (/5)	Cost (/5)	Accuracy (/5)	Total (/20)
Laser Sintering (Nylon 12)	2	3	2	2	9
Material Extrusion (ABS)	3	4	3	3	13
Material Extrusion (Acrylic)	4	4	3	4	15

Table 2. The weighted-matrix study for the three available manufacturing methods

Two cars were manufactured; an initial body on stilts, and the final car without wheels. The former acted as a contingency plan, and a test case for finishing. Communication between the design and experimental teams [1] [4] assisted the decision to mount the second car on bearings, thereby minimising friction and allowing better drag balance readings to be taken. To minimise costs and maximise efficiency, both cars were shelled in Solidworks, creating hollow vehicles of wall thickness 5mm. The models were exported as STL files and sent to CALM, where they took four weeks to be printed.

To achieve a mass appropriate for stable testing in a wind tunnel, the decision was taken to fill the models with plaster. The second (final) model was printed such that bearings could be inserted to act as wheels. In tandem with the parameter test (to minimise aerodynamic drag) it was necessary to reduce friction, particularly due to information from the experimental group, which needed minimal friction for the force meters to be reliable. Research proved SKF bearings (12mm interior, 19mm exterior) to be the optimal available solution.

The final step was to apply a finish to the models so as to make the smoothness of the experimental group's model as close as possible to the smoothness of the virtual model being tested by the HPC group [2] [6]. Once dry, the models were delivered to the experimental subgroup for testing. It was ensured that a member of the design team was always contactable if queries arose.

3.3 Rendering

The rendering process was implemented using Blender 2.69 on a 2.4 GHz Intel MacBook Pro, with 4 GB RAM. In the totality of the project, approximately 180 hours were spent in Blender, of which 20% were light solving. This section first outlines the basic stages of the process, and then details particular important aspects.

3.3.1 Basic Stages

There were seven stages in the rendering process: geometry formation, lighting, UV unwrapping, texturing, rigging, mechanisation, and light solving [20].

3.3.1.1 Process Overview

The first step is to introduce the model geometry. This can either be created by manipulating basic shapes in Blender itself, or by importing surface geometry (STL files) from CAD software such as Solidworks. Additionally, many STL files are available online [26].

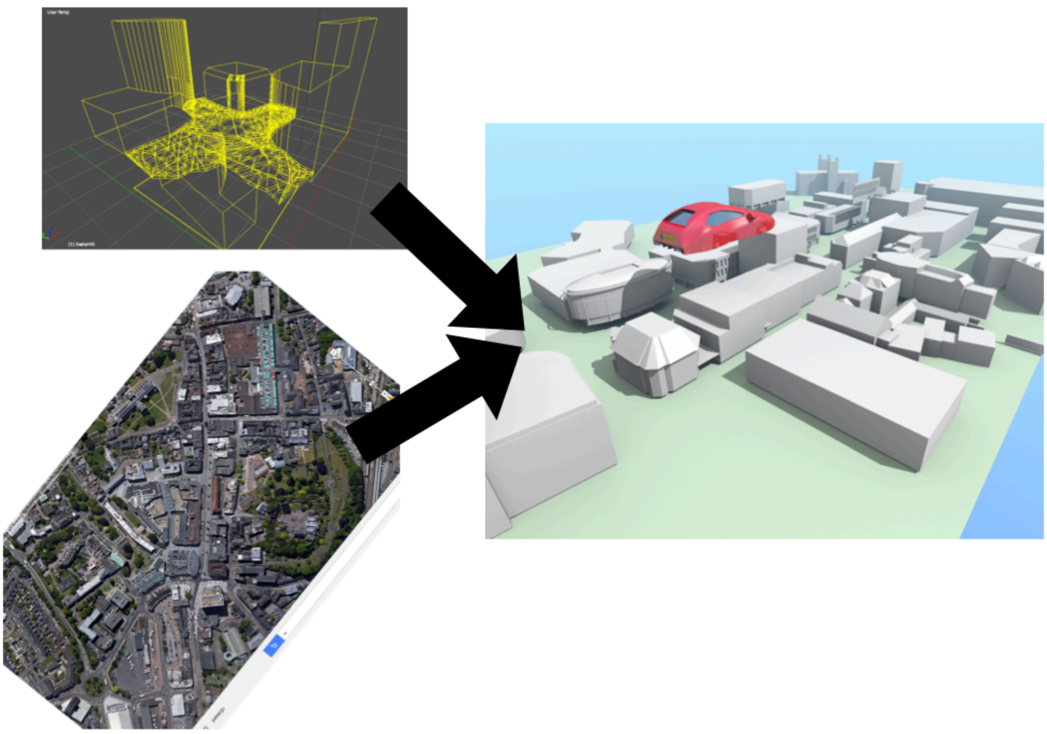


Figure 10. Pooling field data and satellite imagery to create the virtual environment

In this case, the concept car was built in Solidworks (see section 3.1), while the environment initially used surface data collected in a site visit to Exeter [7], which centred on the main intersection in the High Street. Once meshed in Blender, aerial images were overlaid using data from Google Earth [27]. The remaining buildings were then built onto their sites in relation to the original geometry. The method is illustrated in figure 10, and while it provided accurate detail about the width and length of buildings, the heights were intangible, and thus merely estimated from photographs of the area – this is an aspect in need of improvement, as discussed later.

Away from the car, the only objects that could not be formed using primitive shapes in Blender were the trees. A Python add-on was acquired (available online at [28]) that splits branches exponentially. By defining the base size and level of splits, realistic trees can be formed – this project's are shown in figure 11, along with two example buildings. The branches in the uppermost level are flattened to form leaves.

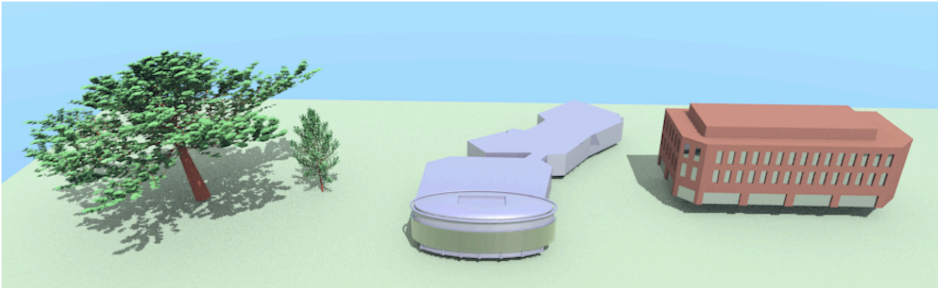


Figure 11. Trees and buildings in the Blender scene

Blender treats the camera like any other object – it can be moved and mechanised like a car, as discussed below. Additionally, light-specific parameters need to be defined; to encompass the whole virtual environment, a wide-angle focal length was defined (equivalent to a 20mm lens in a 35mm camera).

All objects can be scaled, rotated and located, and this information is stored with the mesh. Object rotation can either be defined by local X, Y and Z axis or their global equivalents [21]; for consistency reasons, this project exclusively used global axis for the environment, and exclusively local axis for the car, which would move and rotate within the environment. Figure 12 shows the basic geometry under construction in Blender.

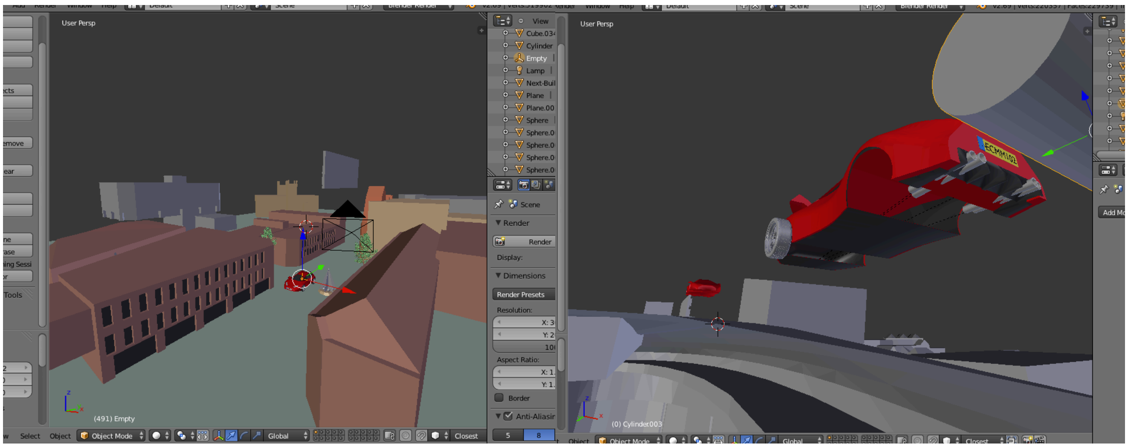


Figure 12. Aligning the basic geometry in Blender, unrendered

Unless specified, there is no ambient light in Blender. All light must come from designated sources; these are either points ("lamps") or objects that have been specified to emit light [21]. Additionally, it is necessary to add a level of interference in the air (what in reality would be equivalently caused by moisture or dust) so as to diffract the light and avoid absolute shadows. For this project an infinitely-far lamp was defined, thus emitting parallel light as the sun (approximately) does [19].

To apply an image or pattern to an object's surface, the three-dimensional shape has to be UV-unwrapped. This is the term for projecting a three-dimensional surface onto a two-dimensional plane, as illustrated in Figure 13. (In standard parlance, the x, y and z axes refer to the three dimensional coordinates; therefore the letters u and v are used for the projection coordinates, hence the name UV unwrapping [21].) For this project, only objects that needed non-plain surfaces were unwrapped – number plates, signs, etc.

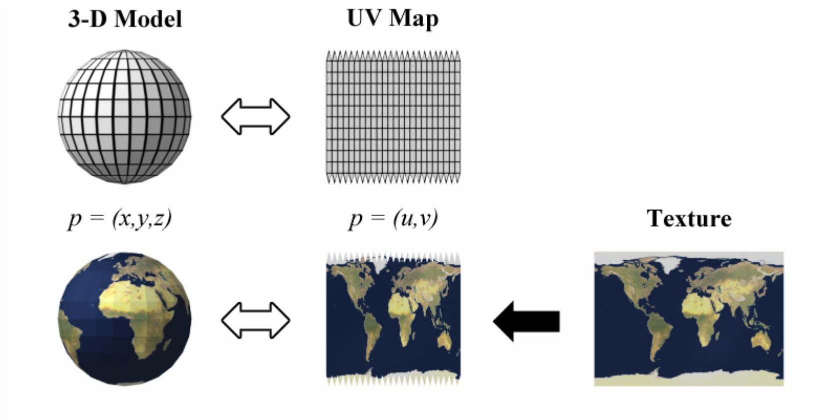


Figure 13. UV-unwrapping a three-dimensional surface into two dimensions

Texturing can be applied to any surface. While not used extensively in this project, texture can be useful for detailed rendering of rough or patterned surfaces. Texture can be created individually, implied by image data, or loaded from a set pattern [21].

To make objects interact with each other, Blender allows objects to be rigged – driven and parented; that is, to define relationships between specified criteria of different objects [21]. Parenting an object to another simply means that any applied rotation, scaling or movement to the parent will also be applied to the child, effectively "grouping" the two. Driving is more complex, and allows an applied alteration to one object to imply another alteration to the second object [21] (while rigging is the term for combining parenting and driving).

For instance, one object moving in the local x-axis will cause the other to rotate around the y-axis, at a specified conversion rate. Rigging and parenting are often combined to mimic physical interactions (in essence, rigging is an extremely simple physics solver); in this case, the car body is parented to a defined point (an "empty"), and the wheels are rigged to the car body such that movement in the local x-axis (or whichever axis is equivalent to the forward/backward trajectory of the car) translates into wheel rotation around the y-axis (or whichever axis is equivalent to the wheel axle). Thus if the car moves, the wheels turn. The relationship can be defined because the distance the car travels in one wheel turn is equal to the wheel circumference 2πR (where R is radius); the scripted expression for the concept car is shown in equation 1, and illustrated in figure 14.

$$Y_{rotation} = \frac{X_{location}}{2\pi R} = \frac{X_{location}}{3.77}$$

Equation 1. The relationship between local x-axis location (in metres) of the car body and local y-axis rotation (in radians) in the car wheels

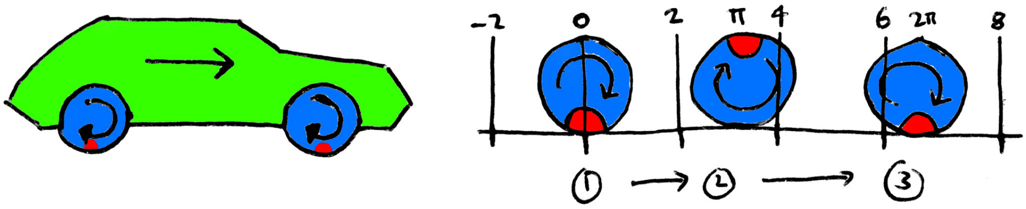


Figure 14. The relationship between body location and wheel rotation is dependent on the radius of the wheels

For animation, the objects in the scene need to move and interact. Movements are defined by inserting object keyframes at specific points in time. Three variables can be defined in a keyframe: location, scale and rotation, or any combination of the three [21]. The transition form (i.e. linear velocity, or as a function of time) can be defined for each action. For this project the main car was rigged (as mentioned above), so only the "empty" needed keyframes. Separately, the body was rotated around the local y-axis so as to mimic real suspension when the car went through high acceleration or deceleration.

The final stage of the render is light-solving, where Blender integrates the light with the scene to output an image. Before implementing the solver, the camera properties must be specified; these include aperture, depth of field, f-number, frame rate, sensor size, and other criteria [21]. There are three methods of light solving in Blender: Game, Blender Render (BI), and Cycles. The first is a low-quality, high-speed render, useful for real-time rendering in games, but not for this project. BI is a surface-based solver, which takes each viewable surface mesh element and works out the light reflected on its primitives (primitives being the edges and nodes used to define the surface), and averages these to find the surface light. The third, Cycles, is the most powerful, and works on a pixel-by-pixel basis, tracing the light path "backwards" from the camera to any surface, and following the diffracted light particles to their original source. Because path tracing is unbiased and physically based, the result is a more faithful-to-reality image [21].

Rendering the concept car in the High Street in a 3000x2000 PNG file took between 10 and 15 minutes, which translates as up to 60 hours for a 10 second movie. For this reason smaller, faster resolutions were used for animation.

The final Blender scene consisted of 157 objects, 2.2 million faces, and 310,000 leaves. It is shown in figure 15, unrendered.

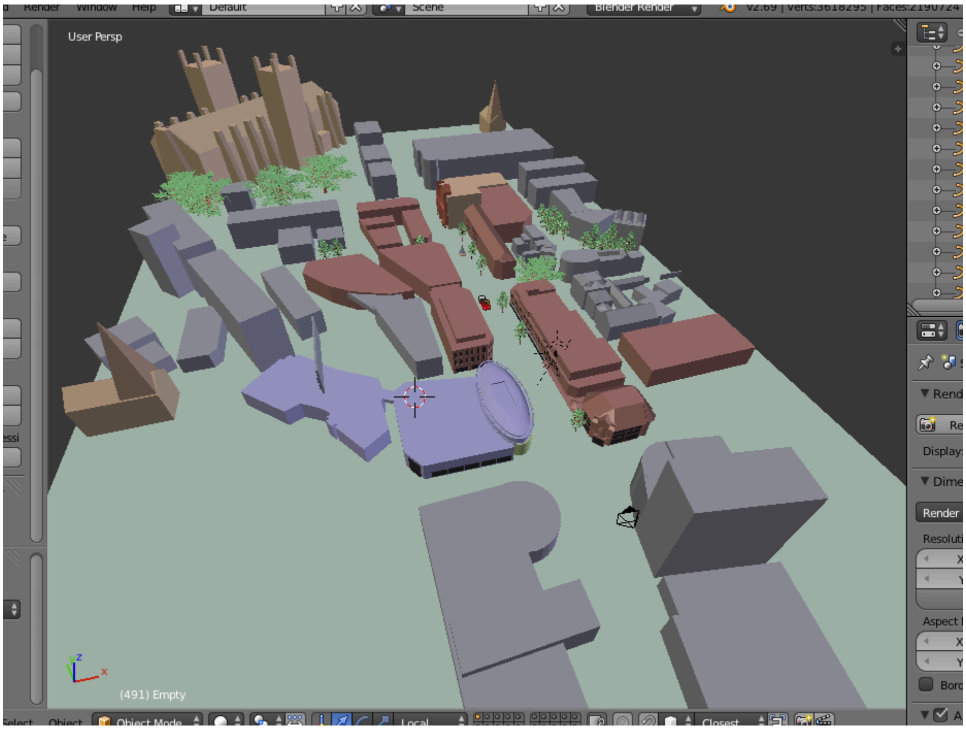


Figure 15. The final scene in Blender, unrendered.

3.3.1.2 Mesh Comparison

Figure 16. Smoothing a non-ideal mesh can result in blocky topology

To achieve optimal renders, the mesh needs to be as representative of the original model as possible, while being finite. The original mesh (which was delivered to CALM for ALM) is suitable for manufacture, but under rendering can create adverse lighting effects. Blender solves meshes in two ways: flat or smooth [21]. A flat mesh literally interprets the surfaces as perfectly flat and results in a non-promiscuous render, but can lead to the “glitter ball” effect [19]. A smooth mesh interprets the surface and its neighbours and averages the topology into a curve (solely in the light-solving process). Due to some non-ideal elements near the base of the vehicle, this could result in a blocky mesh as in figure 16.

Blender has two modifiers for dealing with non-ideal meshes; the surface can be remeshed into quadrilaterals, or existing quadrilateral meshes can be smoothed using a Gaussian algorithm. Since the latter is not applicable to the concept car mesh without the former, it was necessary to perform a study to determine the best remeshing option. Remeshing can be performed on any input surface, and creates a quad-based topology based on either sharpness, smoothness or blocks, neatly illustrated in figure 17.

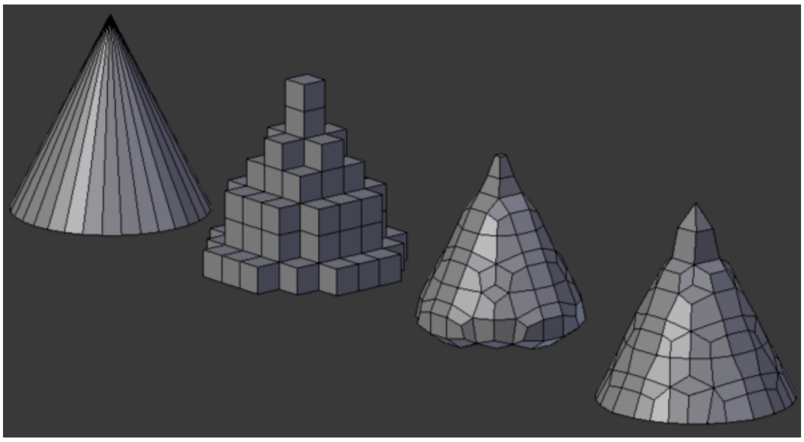


Figure 17. Remeshing a cone into three variants of a quad-based mesh; blocks, smooth and sharp (L-R) [29]

The process depends on the octree depth (octree refers to a data structure where each node has exactly eight children – effectively, the higher the octree depth the greater the three-dimensional resolution [30]). By creating a smooth, non-mirror, ideally-meshed surface and then remeshing it in each variation for increasing octree depth, it is possible to find the fastest method for the car in question. A smooth part of the car’s bonnet was isolated and made absolutely red (R:255, G:0, B:0) and then rendered under an infinitely far white light. The render was then exported to Adobe Photoshop and averaged to find the overall colour. This was performed for each remeshed car at octree depths 1 – 9. Better meshes exhibit more red light, while poor meshes will exhibit less. The results are shown in figure 18. From the results it is clear that all three remeshing modifiers achieve greater fidelity at greater octree depth, but the effect on CPU usage is dramatic – by definition, one global increase in octree depth increases cell count by 700%, though this can be mitigated by limiting octree expansion to areas of interest.

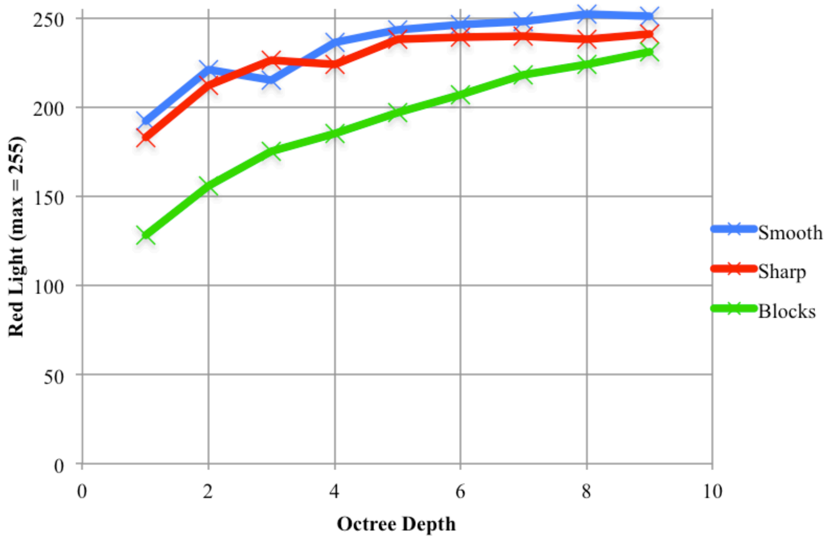


Figure 18. The level of red light emitted by remeshed object, indicating smoothness and fidelity

From a depth of four octrees the smooth remesher performed best, so the concept car was remeshed in a smooth topology at octree depth eight. Figure 19 shows the car in five basic meshes: flat, smooth, smooth remeshed, sharp remeshed and block remeshed.

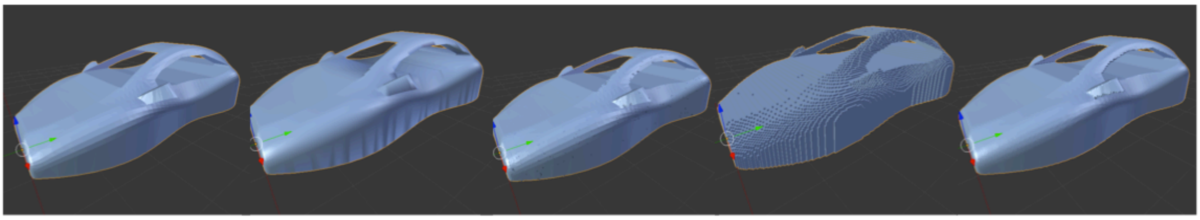


Figure 19. Comparison of the concept car flatly meshed, smoothly meshed, sharp remeshed, block remeshed, and smooth remeshed (all remeshing at octree depth 6)

Once remeshed into a quad-based mesh, it was possible to smooth the car to achieve optimal reflective and optical properties for the render. Smoothing works by applying a blurring Gaussian function. A Gaussian function works by altering the characteristic (in this case height and angle, but alternatively colour or another parameter) of each cell in relation to the surrounding cells [31]. In a one-dimensional scenario each cell has only two neighbours, while in a two-dimensional scenario each cell has eight neighbours, and the transforms are shown in equation 2. (In a three-dimensional scenario each pixel would have 26 neighbours, but this mesh is surface based.) The strength of the smoothing modifier is defined by the "reach" of the Gaussian function (typically each cell is only influenced by pixels within 3-4 standard deviations) and the magnitude of any difference [31].

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}} \qquad G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

Equation 2. The Gaussian function in a one-dimensional (left) and two-dimensional (right) mesh.

The smoothing modifier significantly improves the quality of the mesh, as illustrated by the pre and post-smoothing concept car in figure 20.

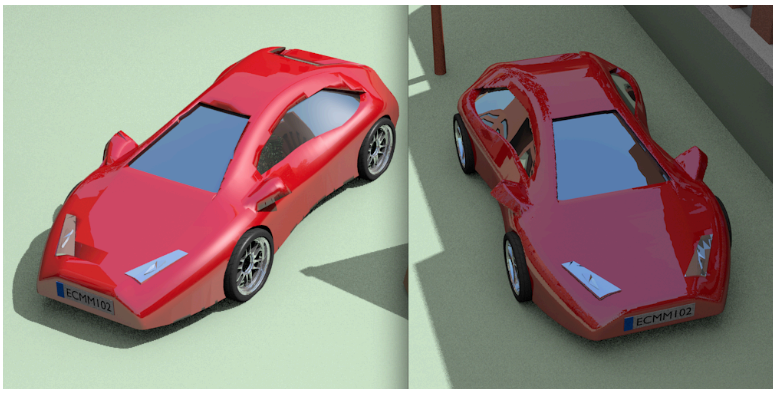


Figure 20. The concept car rendered before smoothing (left) and after (right)

Simulatenously to this project, the HPC group [2] [5] [6] was optimising meshes for CFD analysis. In theory, this would be useful for good rendering, but the dynamic nature of their development made time an obstacle. Additionally, it was valuable to render using no more information than given to the CALM laboratory, for comparison of the render (manipulated only with Blender) with the physical models.

3.3.1.3 Mesh Correction

Despite all the efforts of remeshing and smoothing undertaken above, there remained some visible imperfect edges on the concept car. These were tackled on an individual basis, using Blender's vertex manipulation tool to alter the individual cells. Figure 21 shows such an alteration to triangular cells on a pre-remesh area.

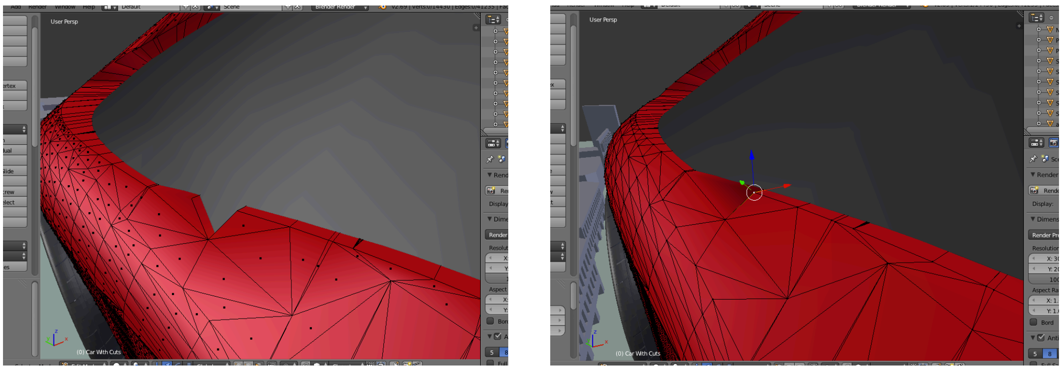


Figure 21. Transforming the individual vertexes to improve the mesh

3.3.1.4 Light Solving Comparison

As discussed theoretically in section background, there are two main ways to light solve in blender. In practise, cycles demonstrates truer behaviour in reflections and distortions, as shown in figure 22.

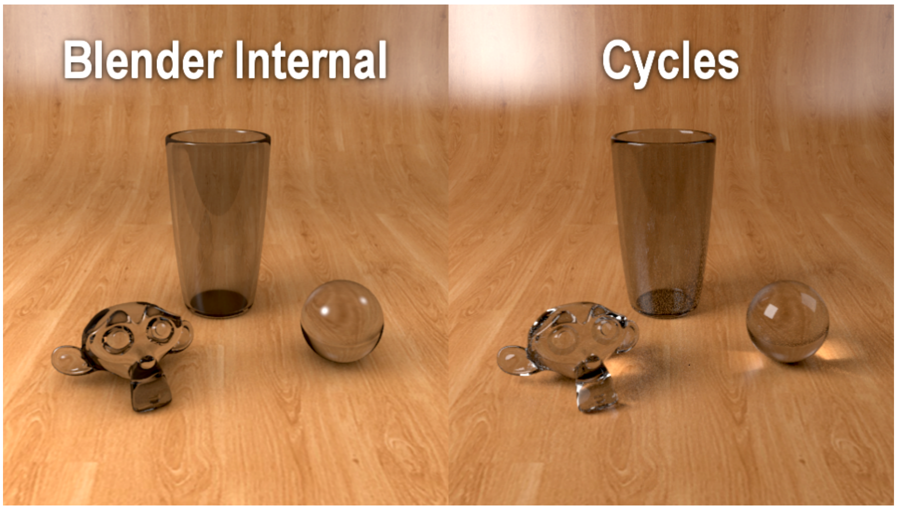


Figure 22. Comparison of different light solvers on some Blender primitives. Note the diffracted light below the two front objects in the Cycles render [32]

To determine the feasibility of the more powerful Cycles render, a simple test was performed on the basic concept car. It was rendered at increasing resolutions in both BI and Cycles, and the light solving time was recorded. The results are shown in figure 23. On certain scenes, Cycles took 17x longer than BI.

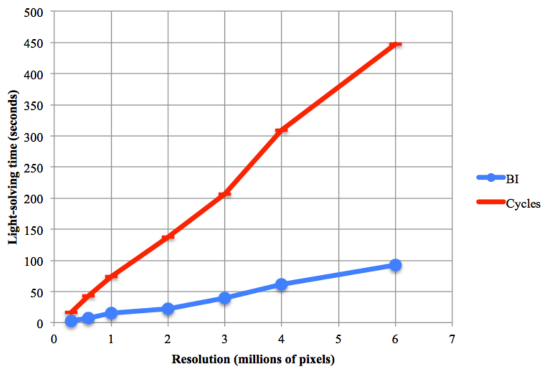


Figure 23. Comparison of light-solving duration under BI and Cycles rendering

3.4 Python Scripting

Blender is partially written in Python, an object-orientated, general purpose programming language [33], to allow the user to construct and run scripts to create or customise tools, imply logic, execute tasks, export and import data, and automate procedures [21]. The programme is also written in C ann C++ [21].

On loading Blender the default scene is blank save for a cube. Due to the repetitive nature of rendering, it was deemed useful to develop a Python script to automate the importation of the concept car mesh and combine it with an STL file of Exeter (created for this project with data from [7]). As well as time saving, scripting allows a greater degree of control over tools where a GUI is insufficient or subjective [21].

4.0 Results

Following the deliverables outlined in section 2, there are three distinct results, as outlined below: a pair of virtual concept car designs, two testable ALM models, and rendered images of the final model. The latter also resulted in a Python script.

4.1 Concept Cars

The two concept cars are shown within SolidWorks in figure 24. From here they were sent to the University's CALM laboratory (with some alterations) for manufacture, and electronically to the HPC group for virtual testing. From the RANS CFD analysis the concept cars were found to have drag coefficients of 0.32 and 0.27 respectively.

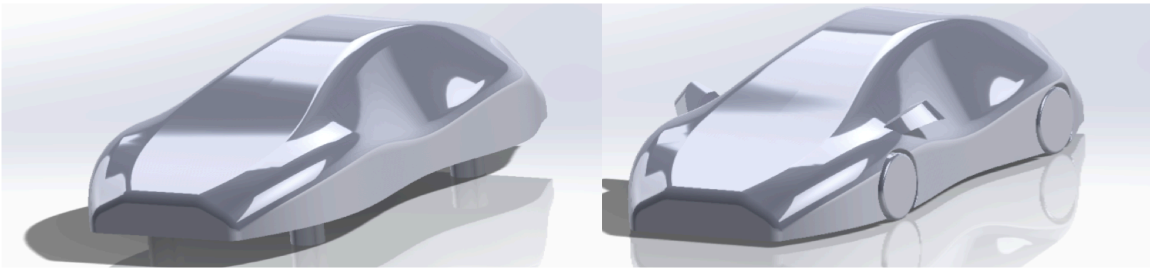


Figure 24. The CAD models within Solidworks

4.2 Manufactured Models

As per the methodology followed in section 3.2, two shelled concept cars were sent to the University's CALM laboratory for manufacture by means of material jetting. The two models are shown (the second complete with bearings) in figure 25. The finish on the surface is clearly not perfectly smooth, but by definition the ridges are no more than 1mm in height. Using the assumption of a flat plate immersed under flow, this means the roughness is insignificant, as the height of significant boundary layer is greater: 1.25mm [3].

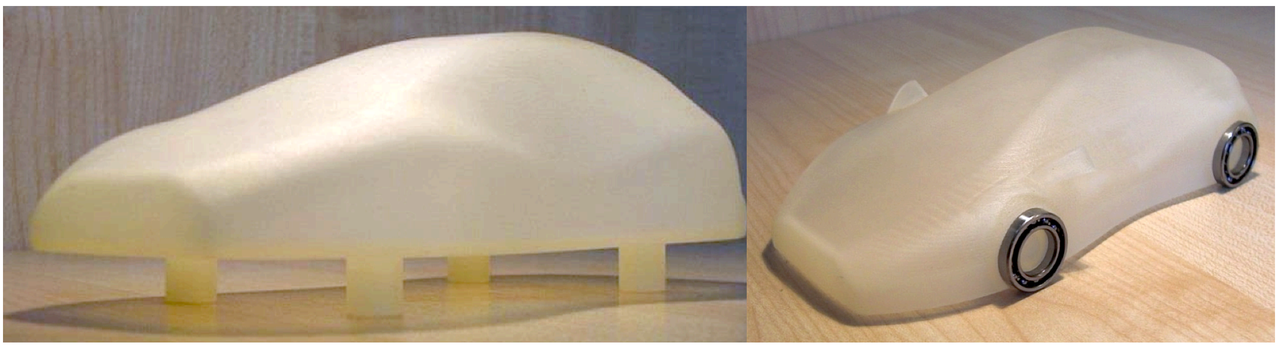


Figure 25. The two models after manufacture, but before finishing or filling. Note the rough finish on the second model.

Once in a stable state, the models were delivered to the experimental group for testing in the newly rebuilt wind tunnel. Readings of the model taken with pitot tubes [4] and anemometers [1] provide a means of comparison with the virtual wind tunnel, tested by the HPC group [2] [5] [6].

4.3 Rendering

Following the method described in section 3.3, the concept car data was combined with field data, and built upon for visual purposes. Materials and textures were created, the lighting was defined, and a virtual 20mm lens camera was deployed. The results were outputted as 4000x3000 pixel PNG images, shown in figures 26 – 28, and as animation, frames of which are shown in figure 29.

Figure 26. First rendered image of the concept car in Exeter High Street, light solving time 7.5 minutes

Figure 27. Second rendered image of the concept car in Exeter High Street, light solving time 12 minutes

Figure 28. Third rendered image of the concept car in Exeter High Street, light solving time 9.5 minutes

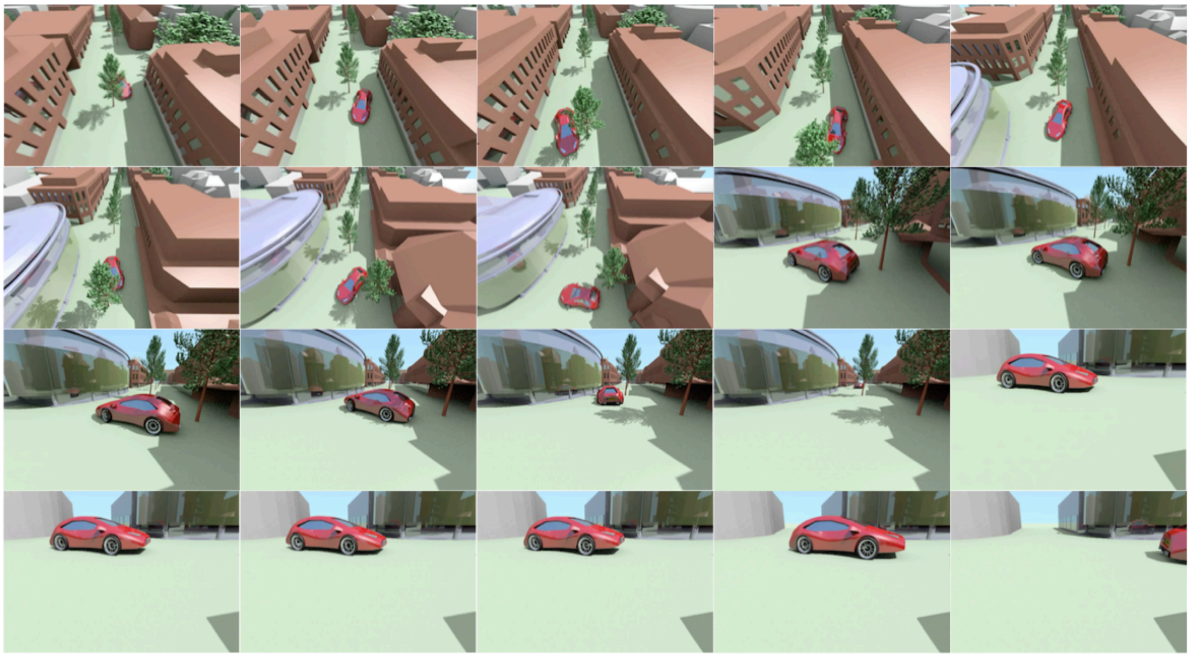


Figure 29. Series of frames from the rendered animation in Exeter High Street

The animated movie and full-resolution images are available at [34] and Appendix A.

4.4 Python Script

As discussed in section 3.4, a short Python script was developed to clear the Blender start-up file and import a car, rotate it, scale it, apply a green paint scheme, import the basic Exeter environment and apply a brick-like material. The script is shown in code 1, but varies depending on your operating set-up. Comment lines are hash tagged.

```
# Virtual Wind Tunnel: Blender Script April 2014

# This loads the standard Blender library
import bpy

# This clears the scene of the standard cube
bpy.ops.object.delete()

# This imports an STL mesh called "car.stl" on the desktop
full_path_to_car = "/Users/edward/Desktop/car.stl"
bpy.ops.import_mesh.stl(filepath=full_path_to_car)

# This scales down the STL model to normal Blender size
bpy.data.objects['Car'].scale.y=0.01
bpy.data.objects['Car'].scale.x=0.01
bpy.data.objects['Car'].scale.z=0.01

# This rotates the model to sit on the standard blender plane
bpy.context.object.rotation_euler[0] = 1.57079633

# This creates and applies a new material, in this case green
(red,green,blue)
paint=bpy.data.materials.new("Paint")
bpy.data.materials["Paint"].diffuse_color=(0,0.8,0)
thingy=bpy.context.selected_objects[0]
thingy.active_material=paint

# This imports the STL mesh of Exeter
full_path_to_environment                                    =
"/Users/edward/Desktop/environment.stl"
bpy.ops.import_mesh.stl(filepath=full_path_to_environment)

# This creates and applies a new material, in this case brick
(red,green,blue)
paint=bpy.data.materials.new("Brick")
bpy.data.materials["Brick"].diffuse_color=(0.5,0.2,0.2)
thingy=bpy.context.selected_objects[0]
thingy.active_material=paint
```

Code 1. A Python script to import, rotate, scale, and colour the concept car, and place it in the High Street

The remainder of the rendering process was too subjective and non-repetitive to justify coding. However, with simple alterations code 1 could apply to other objects. Figure 30 shows the result of applying the code to a simple car geometry available online.

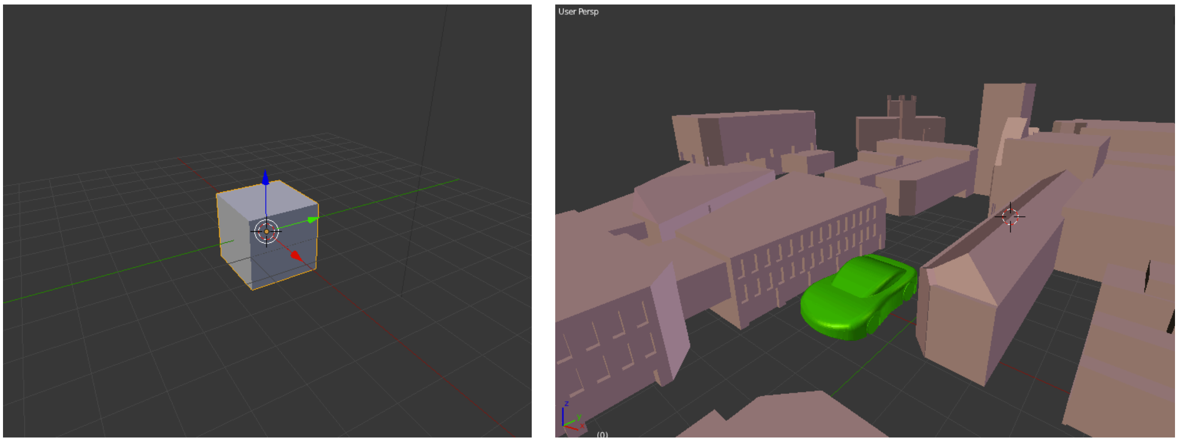


Figure 30. Applying Code 1 to the empty Blender scene, using a simple car geometry (pre-script left, post-script right)

5.0 Project Management

From a non-technical perspective, there were three areas of project management: budgeting expenditures, organising cohesion between teams, and mitigating the health and safety risks posed by different aspects of the project.

5.1 Economic Management

University policy is to allocate £100 per person. The VWT group consisted of eight people, so the total allocation was £800. Because requirements vary from individual to individual, the money was pooled. Table 3 shows the breakdown between groups, and details the design group's portion. The budget left a contingency sum of £75.11.

Item	**Cost**	**Quantity**	**Total**
HPC group			£40.00
Experimental Group			£571.89
Design Group:			
Initial concept car ALM	£117.03	1	£120.15
Final concept car ALM	£130.04	1	£126.92
TOTAL			£858.96

Table 3. Budget breakdown for project, with design costs itemised

5.2 Organisation

Due to the high level of cohesion necessary for the group objectives to be achieved, there was a strong effort to coordinate organisation. The project ran from early October 2013 to the end of April 2014, over which all work was planned on a Gantt chart (see figure 31). The first chart was altered after initial research changed the anticipated lengths of time for some items [35]. Using the Gantt chart allowed for planning of tasks weeks ahead, and emphasised where inter-group deliverables needed to be met.

Meetings were held each week so as to update the group on progress and tackle any issues, with the supervisor present. The team operated a rotational system whereby a different member would perform the role of secretary each week, and the next week that member would chair the meeting, and so on. After several full rotations, the role of chair was permanently awarded to one member for greater continuity, while the role of secretary continued to rotate. The secretary took meeting minutes in the group logbook, and distributed them for the next week. As well as individual logbooks for personal use, there was a collective logbook for recording proceedings and formalising suggestions from academic or industrial experts.

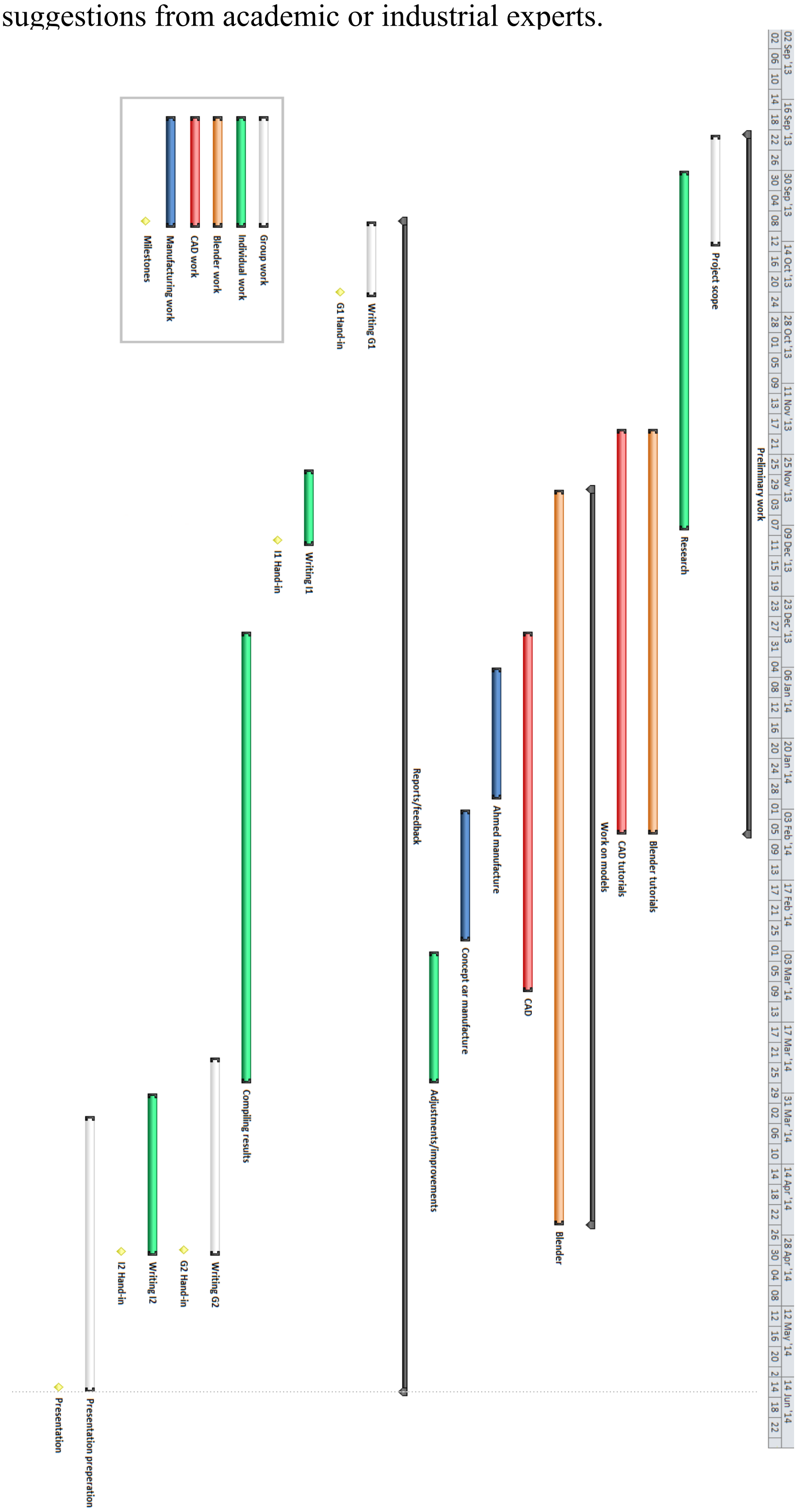


Figure 31. The Gantt Chart used for scheduling individual project work

Outside the weekly meetings, communication was through email and a networking website, and a file-sharing hub [36] was set-up for greater collaboration. In the final weeks of the project there were near-daily meetings in the university.

To gain advice from a different perspective, there were a number of visits by academics from outside the university. For the individual aspects discussed in this report, there were meetings with a PhD student familiar with the Blender interface.

5.3 Risk Management

At the outset of the project a risk assessment was performed for all aspects of the project. It was routinely updated to reflect new aspects emerging. The ultimate table is shown in table 4. None of the risks came to pass in full, but there was an error with the University license for Solidworks in the final weeks, which jeopardised the conversion of some topologies to meshes. Thanks to the risk table alternative software was already found and useable.

Risk	Effect	Severity (1-5)	Likelihood (1-5)	Action taken
Computer failure	Loss of virtual model, mesh, renderings, reports	3	3	Backed up work on multiple servers (cloud-based and local). Prepare contingency plan with alternative software
Manufacturing accident	Personal injury, loss of models	4	2	Wore coats, goggles, followed safety literature
Python script error	Incorrect model importation, delays, bad rendering	3	3	Good coding practice, “save as copy” on each modification
Repetitive strain injury	Personal injury, inability to complete project	3	1	Hand exercises, avoid “block” typing
Exhaustion	Personal injury, delays	2	1	Avoid “block” work
Dehydration	Personal injury	2	1	Drink water while working

Table 4. Risk analysis and actions taken

6.0 Sustainability

Sustainability means to meet the needs of today without impinging upon the needs of the future. In the context of this report, this refers to the use of raw materials (mainly fossil fuel based) and the emission of greenhouse gases (mainly carbon dioxide) [37]. Greenhouse gases cause the sun's energy to reflect back down from the atmosphere and dissipate their energy as heat. The warmer air changes the Earth's ecological systems and could contribute to rising sea levels or other effects [37]. The project had significant implications on sustainability within the automotive industry, and incurred environmental impacts of its own. These are detailed below.

6.1 ALM

Not just in the automotive industry, but also in any manufacturing process, ALM provides a means for making businesses more sustainable. Airbus have begun to introduce ALM parts onto their planes, and say that ALM "results in lighter parts, with shorter lead times, fewer materials used during production and a significant reduction in the manufacturing process' environmental footprint" [28]. Clearly the aviation industry has a significant economic interest in minimising weight, but the reduction in material use and energy has economic and environmental benefits to all industries. ALM can more than halve raw material use, and reduce energy use by as much as 90% [28].

In wind tunnel testing there can be significant weight savings because the car body does not undergo high stress. Processes such as Stereolithography (photo curing resin), Selective Laser Sintering (thermoplastics) and 3D Printing (composite of plaster and resin) can all achieve the desired results. Selective Laser Melting is slower and uses more energy but results in stronger products, and would be useful for incurring some of the benefits of ALM while mitigating loss of strength [39].

The differences between ALM methods are mostly insignificant on the scale that this project delivered. Larger models would need more material for size, and to increase strength to support the higher mass, making energy use per unit mass more important. However, there is an opportunity to use materials that can be melted down and recycled after testing, reducing raw material consumption.

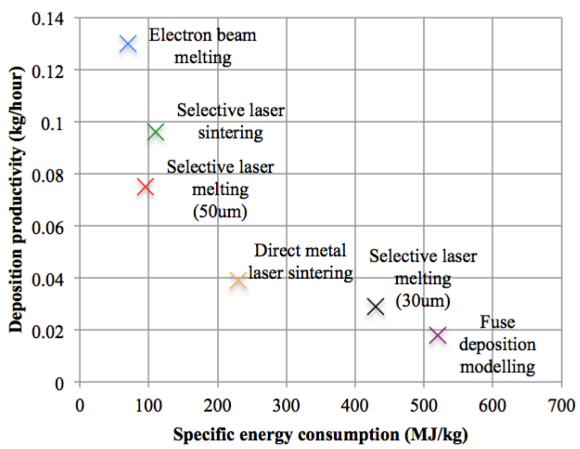


Figure 32. Comparison of productivity and energy efficiency in ALM processes

As with all economic choices, there is a trade-off between different qualities. A study [39] of a selection of ALM methods confirms this, and the results are plotted in figure 32, which shows that Electron Beam Melting is the most efficient process, but not rapid. There is an additional drawback: it can result in a rough “staircase” mesh, which requires a secondary finishing operation to make it suitable for wind tunnel testing [39].

There is another, less tangible aspect of ALM sustainability. A truly sustainable product is one that maximises economic and social gain while minimising harmful effects to the environment [40]. Thus a sustainable product can be developed by having “desire longevity” (i.e. it remains useful/attractive for the consumer for a long time), and creating an attachment between the product and buyer, because an attachment increases the product’s life and therefore reduces the negative impacts on the environment. Because ALM allows flexible designs and mass-customisation, it offers the ability to create such desirable products [40].

6.2 Industrial Implications

The project has shown that VWTs can be an alternative solution to wind tunnel testing, and bring the benefits of measurability, reduced costs and reduced time, improving the eventual product through better and more sustainable production. Furthermore, it allows the iterative approach to be deepened. Particularly at high speeds, the main component of drag on a vehicle is aerodynamic drag (see figure 33), and thus the ability to reduce the drag coefficient (which has a direct impact on aerodynamic drag [41]) would improve efficiency, be that as reduced noise, higher speed, or lower carbon emissions.

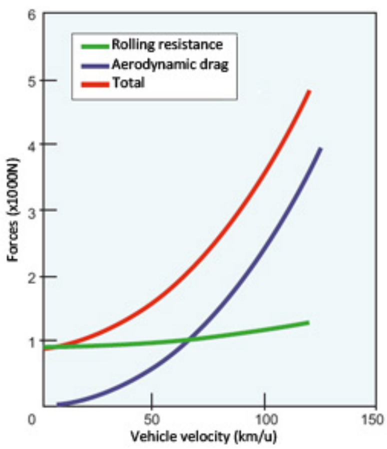


Figure 33. Components of drag as functions of vehicle speed [42]

6.3 Rendering as an Alternative

As shown in the results section, rendering can produce near-photorealistic images based on light solving on model data, and can be useful in the automotive industry for producing images for promotional purposes. In such it is a viable alternative to photograph a real car in a real place. While the savings are ostensibly small, promotional photoshoots can take days of work and involve shipping cars or goods long distances, all of which incur energy consumption. Moreover, rendering has a particular sustainability advantage in larger-scale scenarios, such as a fleet of aircraft or in a recreated explosion.

6.4 Project Energy Use

The ALM process used was material jetting, which has an approximate energy consumption of 520 MJ/kg [39]. The concept car had a mass of 50g and therefore had a manufacturing energy cost of 7.2 kWh – industrially insignificant.

In producing the concept car, this project facilitated the development of a VWT and the rebuild of a physical wind tunnel. Running either one incurs energy consumption. The new wind tunnel has a power rating of 4.2 kW and ran for 100 minutes to test the concept car, therefore consuming 6.8 kWh in total [4]. The equivalent tests in the VWT took 144 hours, but the sampled simulation power consumption was 260W, resulting in a total 4.7 kWh energy consumption – about two-thirds of the experimental [4]. Factoring in the lack of energy needed in manufacture, and it is clear the VWT incurs a significant energy saving.

Rendering was done independently of the VWT or experimental setup, on a 2.4 GHz MacBook Pro, which recorded a maximum power reading of 25W, though the average was around 14W. Light solving alone took approximately 20 hours, incurring 0.4 kWh energy consumption – a negligible amount.

7.0 Future Work

Though delivering on its objectives, the project leaves myriad opportunities for future work. These range from improvements (more accurate, detailed rendering) to industrial applications (developing more efficient cars) and new avenues of exploration (investigating the unique urban airflow over Exeter from the Blender mesh). This section details the main possible opportunities.

7.1 Utilisation of Render Environment

7.1.1 Urban Canyon Flow

Walton [7] has investigated urban canyon flow by measuring building heights and airflow at the intersection in Exeter High Street. The data was used as foundation in this project for constructing the virtual Blender environment. There is an opportunity to feedback the urban data (which has been built upon using the tools in Blender allied with satellite imagery and ground photos) into a far broader, more detailed analysis of urban air behaviour.

7.1.2 More Detailed Environment

The extent of detail in the Blender environment was limited by time and CPU constraints. Indeed, towards the end of the project, as the scene approached 3 million faces, a single still render could take upwards of 15 minutes, and navigation in the unrendered scene became exceptionally slow. The HPC group had access to 12 cores @ 3.47GHz [2], which would enable faster rendering of a more detailed environment.

To maximise the detail in the final render, complicated light scenarios (diffraction, reflection, etc) were limited to the area of interest; the High Street and intersection. More computing power would enable good rendering throughout the city. Furthermore, the heights of the buildings

7.2 Extension of Python Script

There is potential for a far more detailed Python script, which would allow any car to be brought in and then animated and rendered in Exeter automatically. The reason this was not developed is that different cars have different centres of gravity and wheelbases, preventing rotations and alignment from occurring correctly without human intervention. Furthermore, it was not possible to acquire more detailed knowledge of scripting in the timeframe. Greater knowledge of Python, coupled with a geometric analysis (perhaps linked to a spreadsheet) could identify the wheelbase and position the wheels to fit the car in question.

7.3 Render Mesh from HPC

Other areas of the VWT project have focussed on optimising meshes for advanced CFD analysis. It was impractical to render using those meshes because they were being developed as the project progressed, limiting time, but they could now be used to perfect the rendering of the body in Blender.

7.4 Further Application of Drivers

Blender provides drivers so that a change in one object's parameter can change another parameter in another object. In this project this was used to turn the wheels as the car moved forward, but that is merely the simplest application. Given more time and CPU, one could theoretically drive the entire engine bay and suspension – the lean of the body could be a function of acceleration, the exhaust could vibrate depending on velocity, or any other variable.

8.0 Conclusion

In conclusion, this project has delivered upon its individual objectives; it has developed an iterative design process and created an optimised virtual concept car using CFD and CAD; it has manufactured the design using ALM, and in doing so exemplified the method's feasibility as an alternative to clay modelling; and it has pooled field data with the concept model to create a high-quality virtual environment within which to render the concept car.

The project has functioned well in the wider team, coordinating data to maximise the quality of the outcome, and delivering the tools and data for the HPC and Experimental groups to achieve their goals. As a whole, the VWT project has shown that there is high value in incorporating VWTs into automotive design – comparable experimental and virtual drag coefficients in a head-on scenario were 0.167 and 0.17 ± 0.015 respectively, demonstrating the ability of a VWT to rival reality. Coupled with measurability, sustainability, and economic advantages, the case for VWTs is strong, particularly on its deployment as a means of iteratively testing designs to achieve maximum efficiency, or any other criteria.

Furthermore, the successful use of Blender to render the concept car in a realistic environment demonstrates the extent that product development can be virtualised. More work needs to be done on mesh improvement within Blender, but this project shows its potential and provides a starting point for future renders; specifically, the Exeter environment could be taken forward and developed into greater detail.

Finally, the author would like to thank Dr Gavin Tabor for his support throughout the year, and the Blender Foundation for providing such powerful open-source software.

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10.0 Appendix

10.1 Appendix A: Rendering Results

Please find rendering images and video on CD attached

10.2 Appendix B: Other Data

Parameter optimisation Study (angles in degrees):

Rear angle	Cd		Front angle	Drag		Radius	Cd
25	0.634		35	0.644		0	0.322
27.5	0.639		37.5	0.648		1.5	0.198
30	0.638		40	0.685		3	0.185
32.5	0.66		42.5	0.739		4.5	0.16
35	0.647		45	0.758		6	0.152

Octre depth vs redness (out of 255) study:

Octree depth	Smooth	Sharp	Blocks
1	192	183	128
2	221	212	156
3	215	226	175
4	236	224	185
5	243	238	197
6	246	239	207
7	248	240	218
8	252	238	224
9	251	241	231

Resolution times study (resolution in millions of pixels):

Resolution	BI (s)	Cycles (s)
0.3	3	16
0.6	7	43
1	15	74
2	22	137
3	40	207
4	62	309
6	93	448

University of Exeter coursework header sheet

ECMM102 Group Project (Meng) (A, TRM1+2 2013/4)

007854

1014066

600017271

Coursework: I2: Log Book
Submission Deadline: Thu 1st May 2014
Personal tutor: Dr Liang Hao

Student's word count:

By submitting coursework you declare that you understand and consent to the University policies regarding plagiarism and mitigation (these can be seen online at www.exeter.ac.uk/plagiarism, and www.exeter.ac.uk/mitigation respectively), and that you have read your school's rules for submission of written coursework, for example rules on maximum and minimum number of words. Indicative/first marks are provisional only.

Feedback may be given on this sheet, or it may be provided in an alternative format, for e.g. by use of a specifically designed feedback sheet, verbal feedback during a lecture/tutorial, online feedback via the module resource page, generic feedback by email. Check with the marker if you are unsure how feedback for the item of coursework will be given

Explanation of mark: Your final mark is based on several aspects of your work. For each criterion, the standard attained (as given in the table below) is indicated, with a brief comment where appropriate. The final mark will not necessarily reflect equal weighting of criteria.

90-100	80-89	70-79	60-69	50-59	40-49	26-39	0-25
1st	1st	1st	2:1	2:2	3	F	F
Outstanding	Exceptional	Excellent	Very Good	Competent	Weak	Poor (Fail)	Incompetent (Fail)

Submitting your work: Student Services Reception (Harrison Foyer) with cover sheet securely attached (unless specified otherwise). For any queries, email harrisonstudentservices@emps.ex.ac.uk.

Late submission: Work submitted after the due date is subject to the procedures and the standard penalty as described on the student website. Where mitigation applies, an application can be made for leniency - tick the box and attach a completed mitigation form MIA (available from Education Office or download from the student web site). Tick to apply for leniency: ☐

Criterion 1 *Marker to enter criterion here:*							
Outstanding	Exceptional	Excellent	Very Good	Competent	Weak	Poor (Fail)	Incompetent (Fail)
Comments/How to improve:							

Criterion 2 *Marker to enter criterion here:*							
Outstanding	Exceptional	Excellent	Very Good	Competent	Weak	Poor (Fail)	Incompetent (Fail)
Comments/How to improve:							

Criterion 3 *Marker to enter criterion here:*							
Outstanding	Exceptional	Excellent	Very Good	Competent	Weak	Poor (Fail)	Incompetent (Fail)
Comments/How to improve:							

General comments/How to improve
General suggestions from the marker on how your work, or approach to your work could be improved (continue over page as necessary):

Overall Mark *All coursework marks are provisional and subject to change at the Board of Examiners*			
First marker	Second marker (where appropriate)	**Final Mark (%)**	Staff signature

University of Exeter coursework header sheet

ECMM102 Group Project (Meng) (A, TRM1+2 2013/4)

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Criterion 1 *Marker to enter criterion here:*							
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Comments/How to improve:							

Criterion 2 *Marker to enter criterion here:*							
Outstanding	Exceptional	Excellent	Very Good	Competent	Weak	Poor (Fail)	Incompetent (Fail)
Comments/How to improve:							

Criterion 3 *Marker to enter criterion here:*							
Outstanding	Exceptional	Excellent	Very Good	Competent	Weak	Poor (Fail)	Incompetent (Fail)
Comments/How to improve:							

General comments/How to improve
General suggestions from the marker on how your work, or approach to your work could be improved (continue over page as necessary):

Overall Mark *All coursework marks are provisional and subject to change at the Board of Examiners*			
First marker	Second marker (where appropriate)	**Final Mark (%)**	Staff signature