**Using machine learning to develop natural, human-like vehicle control**

# HumanDrive

## Digital Twin Case Study

# 1 WHAT ARE DIGITAL TWINS?

## 1.1 Introduction

This paper has been written to inform the reader of some of the work being undertaken in the HumanDrive project in the generation and use of digital twins. The paper covers how a digital twin has been created, the tools used, techniques developed and their application to the HumanDrive project (https://humandrive.co.uk/) (an Innovate UK sponsored project) to date. Much of the focus of this paper is on that of data used in the digital twin, data processing and its ultimate exploitation in creating an accurate real-world digital twin of public roads and the Multi User Environment for Autonomous Vehicle Innovation (MUEAVI) test track (https://www.cranfield.ac.uk/facilities/mueavi).

Digital Twin technology is the concept surrounding the creation of a digital "twin" or replica of a physical asset. Digital Twins can provide valuable, actionable insight into operations and in this case have been used to analyse human driving behaviour and support safety work being undertaken by the TSC in the HumanDrive project.

## 1.2 What is a Digital Twin

A digital twin can be best described as an evolving digital profile of the historical and current state of a physical asset which can include products, processes, people, systems and devices. Such replication of physical assets enables organisations to dramatically improve business performance by knowing the current state of operation and enabling modelling and simulation based on historic data and real time feeds. Digital twins are typically based on large scale, real-time, real-world data measurements across several dimensions. This can be used to create an evolving and developing profile designed to deliver high value insights as to what real-world actions need to occur to improve and optimise a process or product.

The application of digital twins depends upon the stage of the product in the project lifecycle in which it represents. From a high level, there are three main categories of digital twin – Product, Performance and Production. These categories develop and evolve together. This evolution is sometimes known as a digital thread, a term coined by Siemens (https://www.iotworldtoday.com/2017/11/22/digital-thread-link-physical-and-virtual-manufacturing-worlds/). A digital thread is woven throughout the digital twin and brings together all stages in the development of the real-world counterpart.

## 1.3 Product Digital Twins

Product digital twins primarily focus on the virtual-physical connection, which enables the analysis of how a product performs under a variety of conditions. This analysis allows adjustments and modifications to be made to ensure that the product performs exactly as planned once produced. A digital twin in this example enables organisations to make the best possible decisions in terms of product development. Additional to this, development time and costs are drastically reduced since physical prototypes are no longer required. Organisations can rapidly cycle through design iterations and try out design changes within a lean build, measure and learn cycle.

### 1.4 Production Digital Twins

Production digital twins are typically designed to validate how well a manufacturing process would work on the shop floor prior to production initiation. Through using digital twins to simulate the process, organisations can analyse and determine why things are happening and produce a production methodology that remains efficient under an array of scenarios and conditions.

### 1.5 Performance Digital Twins

Performance digital twins are designed to capture and analyse data from operations products and plants to provide meaningful and actionable insights to better inform stakeholders and decision makers. These insights can enable organisations to develop new business opportunities, gain insight to further develop virtual model and improve product and production system efficiency.

### 1.6 How are they currently used?

Digital twins can be used to review, optimise, monitor, enhance and control physical assets such as systems, products or services in a safe, controlled and repeatable manner. An example of this usage includes the maintenance and optimisation of manufacturing processes within automotive, architectural and power generation applications. Digital twins enable organisations to solve physical issues faster by detecting them sooner, predict and simulate outcomes, demonstrate the impact of design changes, reduce costs and ultimately deliver better products and services to end users.

More recently, with advancements in computer graphics, Geographic Information System (GIS) (https://www.esri.com/en-us/what-is-gis/overview) data and 3d modelling, digital twins are used to represent the real world to millimetric accuracy in the form of a digital companion. These companions can be used to review, design, test and validate numerous applications from Autonomous Vehicle (AV) testing through to Infrastructure, urban and architectural design practices throughout the lifecycle of a product or project. Furthermore, thanks to advancements in computing capabilities, the resulting data can be analysed with modern-day massive processing architectures and advanced algorithms to enable and drive a fundamental shift in design processes, which has to date been largely unattainable using current methods.

# 2 HOW ARE DIGITAL TWINS DEVELOPED?

The production of digital twins can be a daunting task for any organisation, especially when taking large scale projects into consideration. The key is to focus in on a small area where a large amount of value can be delivered. However, before any progress is made on the digital twin itself, it is important to firstly understand the desired outcomes from a digital twin, the definition of a digital twin, as well as the approaches and options available during its development.

The development of a digital twin is comprised of the same basic principles across all types of digital twin configuration. The high-level architecture can be defined by the following steps:

### Connect and Collect

Physical assets fitted with sensors which measure inputs, processes and the surroundings. These measurements can be captured and transformed into secured digital messages and then into the digital twin. In the case where the product digital twin is fully integrated into a digital twin of a real-world environment, the create step will involve capturing the physical space using sensing technology such as LiDAR.

### **Communicate**

Communication enables seamless translation of captured sensor data or physical process into the digital twin. This can be achieved through real-time connectivity, or in the case of the analysis of historical data, a database can be created in which to store captured, historical data sets.

### Aggregate

Designed to support the ingestion of data into a repository for use in the digital twin. Data processing can include aggregation, synchronisation and translation to the required format for use in within the digital twin environment.

### Analyse, Alert and Advise

Data is analysed and visualised through interrogation and the use of visualisation tools such as a custom solution within an engine such as Unity (a Real Time Games Engine (RTGE)), or off the shelf Product Life-cycle Management (PLM) software. Machine Learning can be employed at this stage to analyse the data, save time and convert into additional formats which add further value to both the digital twin and the development process.

### Insight, Decide and Optimise

This involves gathering insights through analytics presented through visualisations, dashboard and user interfaces and identifying areas of interest or potentially required investigation or modification.

### Act, Innovate and Transform

This enables actionable insights to be fed back to the physical product or process. This competes a closed loop connection between the physical world and digital twin.

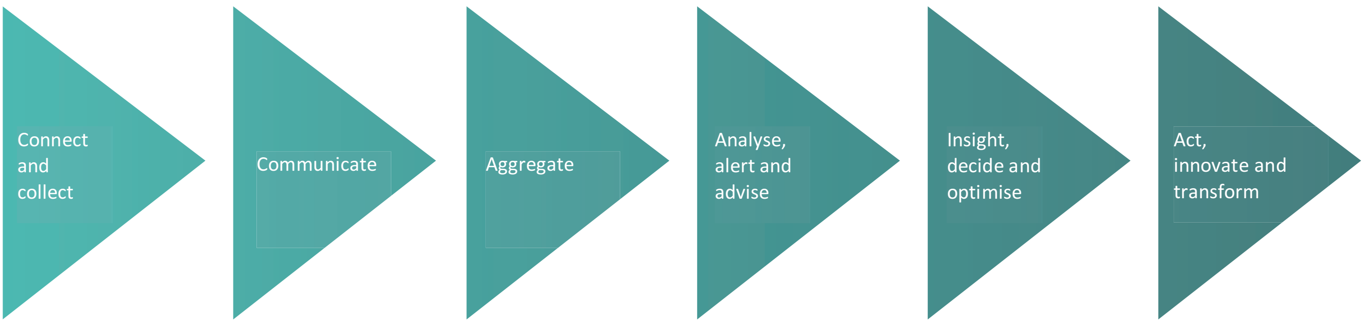



*Figure 1: Six steps to a digital twin*

# 3 APPLICATION OF DIGITAL TWINS TO CAVs

## 3.1 CAV Development and Testing

The UK automotive industry is in prime position to assert a global leadership position in the demonstration, testing, development and deployment of Connected and Autonomous Vehicle (CAV) technologies. Advancements in computing power, sensor technology, Artificial Intelligence (AI) and Machine Learning have enabled organisations to bring these together in a way that has the potential to make driving safer, easier, quicker, cleaner and more accessible. Already more than half of all new cars sold are available with at least one semi-autonomous driving feature, the vast majority of these also feature additional connected technology.

The UK features a world-class physical test environment ecosystem however, to further support organisations working on the development of CAV's, the use of virtual test environments for simulation and testing has been identified to strengthen CAV development.

A virtual environment, or a digital twin of a real-world location or scenario can be used to test for example, a product digital twin within a geospatially accurate replica of a physical environment. Virtual test environments allow digital twins and models to be built up, which require fewer resources and preparation time than that of its physical test environment counterpart. Further to this, production aspects such as testing characteristics, vehicle paraments and environmental features are easily adapted and modified. This enables organisations to enhance any real-world physical testing for example with multiple iterations around a single test point. Real world testing will still be required but when used in conjunction with virtual testing can lead to a richer set of test data being captured. Although this paper is concerned with digital twins, we should not ignore the use of synthetic virtual worlds (i.e. simulated worlds that are highly detailed but not based upon any specific real-world location), these too have a role to play in the testing of CAVs. The key is to combine these approaches in an optimal manner to assist in this instance with CAV test and development.

As manufacturers are under ever increasing pressure to reduce time to market and further optimise products in terms of performance and reliability, virtual prototyping is becoming ever more adopted. Engineers, designers, decision makers and stakeholders can quickly ideate and explore thousands of design iterations without the requirement to invest in the creation of physical prototypes. Multiple requirements and variables can be tested which, would otherwise not be feasible in terms of time and cost. Due to the inherent nature of a virtual environment tests are also safe, controlled and repeatable. The use of digital twins and virtual prototyping early in the design process allows the inclusion and optimisation of the design concept or prototype, enabling designers to spot issues early and resolve them quickly, efficiently and improve overall design quality.

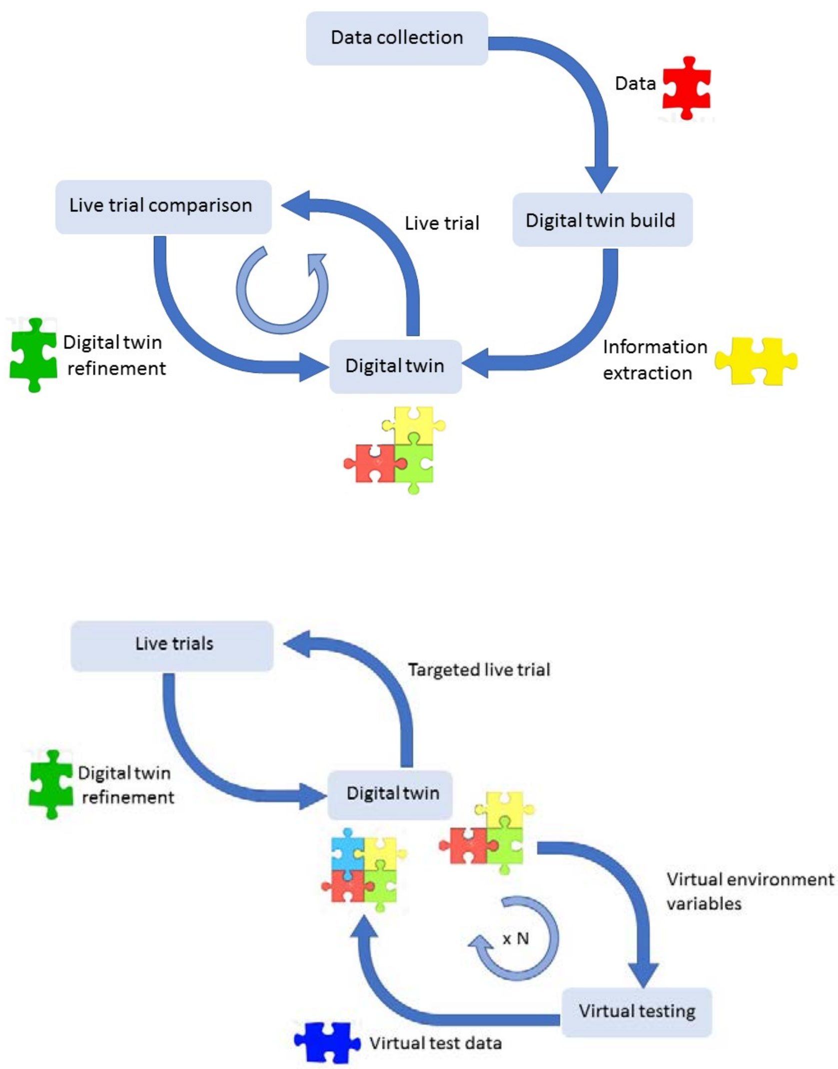



*Figure 2: Digital twin in project testing life cycle*

## 3.2 The Production of Realistic and Cost-effective Digital Twins

For organisations working in the CAV industry to justify and produce a business case to create a digital twin for product testing, the production of such must be cost effective, time saving and ultimately result in a better product. Recently, the creation of digital twins focusing on, but not limited to real-world environments and automotive design has been made much more attainable through the development of computer graphics, processing, survey technology, GIS and 3d content creation.

Under the Human Drive project, a 30-month Innovate UK[1] funded project set to see an AV perform a 200+ mile journey across the UK. A digital twin was produced of a focused area of the real-world test environment to support the project. The digital twin generation was focussed to rapidly demonstrate the value add of a digital twin, within a manageable area yet still ensuring that scalable tools and methods were employed in preparation for large scale digital twin production. Several steps were taken during the process of producing the digital twin, which shall be detailed in following sections.

Before being introduced to UK roads, the HumanDrive AV will be developed and subjected to a robust testing process using a range of facilities, including simulation, hardware in the loop, private test track and small sections of public roads. One of the key innovative aspects of the project will be the development of an advanced vehicle control system. This control system is designed to allow the vehicle to emulate a 'natural' human driving style using machine learning and developing AI to enhance the user comfort and experience.

Ideally for the benefits of digital twins to be fully realised, the development and access to them should be attainable by each company involved throughout the design process. The TSC have started to develop large scale digital twins which could be accessible by any organisation wishing to either test within or develop further. Traditionally, individual companies develop their own digital twins for use within their organisation. This method may be feasible for large organisations with the resources to develop their own bespoke digital twins, however for those organisations with limited resources the ability to share a common digital twin would appear to be an attractive option. The TSC aims to resolve some of these challenges through the provision of methods of processing and utilising data to a common end.

## 3.3 Purpose Behind the TSC Digital Twin

The main purpose behind the digital twin created for the Human Drive project was to enable the project team to better understand human driving behaviour as well as support safety work by understanding the road environment in which the AV is to operate. As part of the development of the AV control system, a series of real-world user trials took place in order to enable the team to better understand the driving characteristics of human drivers, in terms of which factors whilst driving causes drivers to respond in certain ways. The digital twin in this instance is designed to the enable teams of varying expertise and skills such as Human Factors and Customer Experience teams to undertake evaluations of the driving characteristics captured during user trials and to enable the facilitation of subsequent user trials within a data rich and editable virtual twin of the real-world test environment.

[1] Innovate UK are the UK's innovation agency.

### 3.4 TSC Digital Twin Production Method

Several steps were taken during the process of producing the digital twin, which were as follows; Data Gathering, Data Processing, Virtual Environment creation and finally User Interface development. As mentioned earlier, it was important to demonstrate the value and impact of a digital twin within a condensed and manageable portion of the overall test environment. From the added value showcased on small scale, a larger scale digital twin became a viable option using the scalable methods employed within the initial digital twin. By producing the digital twin in manageable portions, it was found that value can be delivered whilst continuing to develop the large-scale twin as well as develop powerful, scalable tools during the process in order to further enable updates and expansion in the future.

The physical test environment is formed of a loop consisting of approximately 20 miles worth of A-Roads and country roads starting at Cranfield University, featuring mixed road surface types, street furniture and the MUEAVI test track (https://www.cranfield.ac.uk/facilities/mueavi). The TSC opted to produce a digital twin of the MUEAVI test track, a smaller section of the test environment to provide quick value, with the larger loop expanding from this in the later stages of development. This proved to be a sensible option in terms of manageable content creation, data gathering and data processing.

# 4 DATA GATHERING (LIDAR, GIS DATA, TRIAL DATA)

All good digital twins start production with gathering of data. As the objective here was to safely test CAV's in a controlled repeatable manner, a digital twin was built of the test environment as a snap shot of the real-world created from Lidar scan technology. The LiDAR provides a high degree of accuracy that was required to reflect the CAVs responses as close as possible to the real test environment.

The primary source of data was a Point cloud captured by Global Navigation Satellite System (GNSS) enabled Lidar. This was chosen due to the high quality of scan equipment the project had access to. It was recognised that similar levels of accuracy can be achieved with photogrammetry rather than lasers (given the right equipment and expertise). However, this would require a mixed ground and aerial approach and potentially additional permissions depending on the scale and location of the scan site.

Since the LiDAR was GNSS enabled, the scan data understood its position in relation to the scanner and the position of the scanner in relation to the rest of the world. Allowing the full environment to be used within a GIS, this provides a plethora of benefits over non-located scan data, some of which are listed below.

- LiDAR can be accurately measured with GIS to error check data and compared with other datasets.
- Analytical methods can be deployed to extract greater data insight, street features for example.
- By tiling the data, it can be broken up into more manageable sections without loss of data integrity.
- The use of Spatial databases allows for increased efficiency when using large datasets.

Historic datasets were used to confirm the validity of some of the captured point cloud.

It should be noted that other, less resource intensive methods and sources of data are available for environments or projects not requiring centimetre accuracy. For example, OpenStreetMap (OSM) (https://www.openstreetmap.org/#map=6/54.910/-3.432) and Ordnance Survey (OS) data can be used as the basis for a digital twin of areas of interest. Using such data sources essentially provides map elements in XML syntax including roads, houses and residential areas. By applying methods detailed in the following sections, organisations can rapidly produce 2d and 3d representations for use in any digital twin type. In many cases, the accuracy of data provided in these formats is enough and is thus could be a smart choice for organisations developing virtual environments for, but not limited to traffic simulation development, urban design and driving simulation purposes.

In the case of our digital twin, features requiring centimetre accuracy such as pot holes and road surface imperfections were of high importance. In this instance, several extra steps are required to firstly gather, then process and eventually utilise the captured data. The following sections highlight the steps taken to produce a centimetre accurate digital twin, however the techniques demonstrated are also of high value whilst producing digital twins based on other data sources such as OSM and OS.

## 4.1 LiDAR

LiDAR is a remote sensing method which uses a pulsed laser to measure ranges of variable distances to the earth. These light pulses are combined with other data such as position to produce accurate, three-dimensional information about the shape of the earth and its surface characteristics. LiDAR depending on design and purpose can give varying degrees of data richness and accuracy. The three main types include Aerial, Bathymetric and Terrestrial (including 2 sub-groups, fixed and mobile). LiDAR can also be used for detection on AVs for object or distance detection as a part of the on-board sensors, it is important to recognise while using similar technology there are differences in the output quality (and price) of a LiDAR CAV sensor and a dedicated LiDAR surveying unit.

For large areas LiDAR is often collected by air, however we opted to use terrestrial mobile mapping LiDAR equipment to generate the most accurate point cloud in terms of surface details of roads, kerbs, verges, street furniture and other surrounding environmental features, as with aerial LiDAR the ground can be obscured by overhanging trees.

## 4.2 Point Cloud

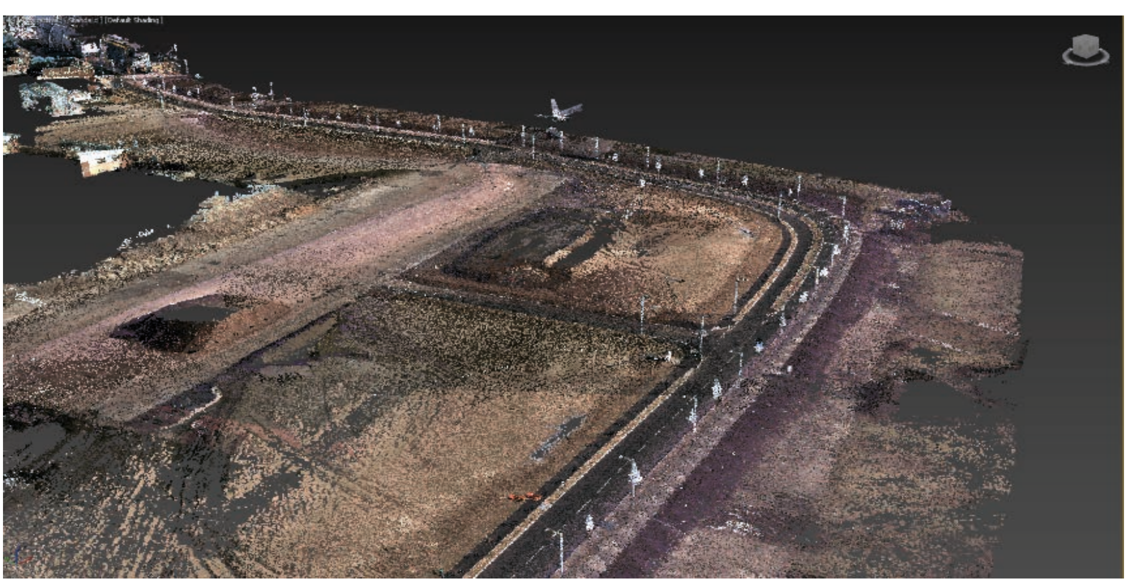


*Figure 3: Sample of captured point cloud*

Point cloud is a set of 3d coordinates that together define the physical shape of an opaque surface. Traditionally, point cloud is considered a very accurate digital record of an object or surface. However, this depends on the capture method resolution and a point cloud file can contain hundreds to billions or more points depending on its resolution.

Point Cloud is often derived from two main methods including LiDAR or photogrammetry. LiDAR where by scanners use beams of laser light and their reflectance to understand the distance to a surface. Photogrammetry is also a popular method particularly with aerial capture platforms from light aircraft and drones. This method relies on overlapping images and the image pixel size information to calculate distances which can be converted into a 3d point cloud mesh. Depending on purposes there are other more specialised methods to generate point cloud such bathymetric mapping with sonar. To achieve the terrestrial, high accuracy purposes in this project ground-based survey quality LiDAR was used.

Since the LiDAR unit uses rays of light to scan the environment around it, points in a point cloud are always positioned on external surfaces of visible objects. Visible objects are defined as object which are not occluded by another from the position of the scanner.

*Figure 4: Sample of captured point cloud*

It is important to note that point cloud is a set of unrelated points with a defined position and colour (usually Red Green Blue (RGB)). On one hand, this makes point clouds (depending on file size) quite easy to compute, edit, display and filter. On the other hand, the downside of this is that the point cloud interpretation process typically requires human involvement which can be costly and time consuming. As part of the HumanDrive project, the TSC have developed techniques which not only reduce the time and cost associated with interpreting Point Cloud, but also drastically reduce the time and cost associated with the development of digital twins based from such data. This process is detailed later in this paper.

The Point Cloud used within the project data was gathered for the TSC by MK Surveys, a Milton Keynes based company using Leica Geosystems LiDAR technology (https://mksurveys.com/mobile-mapping). The result of the LiDAR scan is a Point Cloud covering the entirety of the real-world test environment, to within 2cm positional accuracy. MK Surveys removed most of the unnecessary noise from the point cloud as well as removing both parked and moving vehicles. This process was conducted prior to the delivery of the Point Cloud to TSC to avoid unnecessary bloating of file sizes and potential distractions for the techniques implemented to analyse and process the data further along the workflow pipeline. The focus in this instance was on the static environment, with an emphasis on the road surface.

## 4.3 GIS Data

Environmental Systems Research Institute (ESRI) describes GIS as the following;

> **"A GIS is a framework for gathering, managing, and analysing data. Rooted in the science of geography, GIS integrates many types of data. It analyses spatial location and organizes layers of information into visualizations using maps and 3d scenes. With this unique capability, GIS reveals deeper insights into data, such as patterns, relationships, and situations – helping users make smarter decisions."**

TSC have employed techniques and methodologies used within the GIS industry in many ways throughout the project. For example: Data management, Point Cloud feature recognition and extraction, Co-ordinate system consistency and the sourcing of map data to support the Quality Assurance (QA) and Virtual Twin development processes. In post processing the data the use of Spatial Databases was made to sort, create, query and serve the processed data to the visual interface.

The use of GIS enables us to tie the various datasets together for comparison and analysis. The combined use of GIS, Real-Time Graphics Engine (RTGE) and CAD design tools also starts to move into the newly expanding area of Geo BIM (Building Information Modelling) with the GIS providing a single source of truth to match multi-dimensional data beyond 3d (such as 4d – time, 5d – material, 6d – cost, etc) to real world position. While not designed to be a true Geo BIM solution the workflow developed has potential and wider implications within this space.

## 4.4 Data Processing

### 4.1.1. Point Cloud

Point Cloud data was pre-processed by MK Surveys using Hexagon Cyclone software prior to transfer, this reduced noise (passing cars and erroneous readings) and extreme outliners within the data. The cleaned Point Cloud was provided in several formats including LAS, XYZ and RCP. RCP (Autodesk Recap) was the most appropriate in terms of the format's usability within Autodesk packages and our 3d Modelling package of choice, 3DS Max. LAZ (open LiDAR format) was the most useful for use within the GIS systems including both commercial and open sources tools (such as PostGIS and QGIS). For use within the ESRI stack of software consider converting LAZ to the optimised ESRI open standard LASD.

The first complexity when dealing with LiDAR over a vast area is the large file sizes, GIS/Geo-spatial databases enabled the data to be tiled (broken up into smaller geographic chunks) that can be processed more efficiently and then put back together, often preventing memory errors.

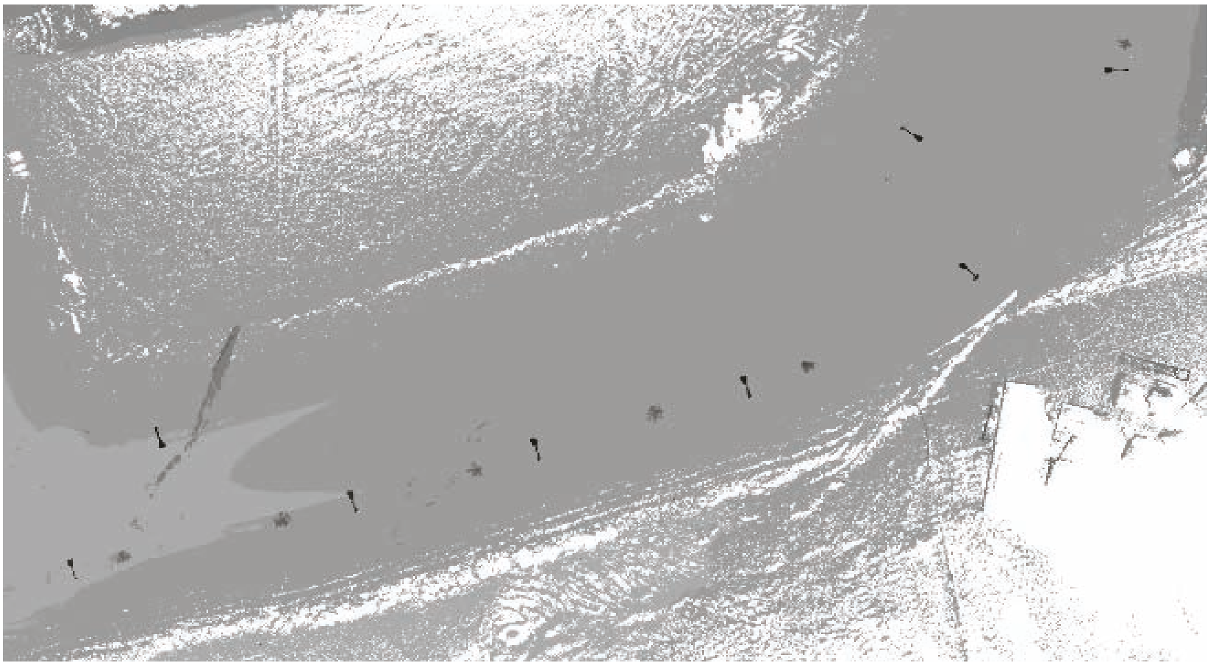


*Figure 5: LiDAR data converted into 2d image based on max height value. Noticeable black lines are lamp posts.*

Positioning environmental features is a challenge This was overcome though a process of converting the (3d) point cloud to a (2d) raster format, a process known as rasterization. Enabling image classification techniques to be used on derived LiDAR values held within the image. Such as images for Max – Maximum height within a given area, Min – Minimum Height within a given area, Density – Density of 3 dimensional points within a given area, Intensity – The light reflectance intensity value of materials during the scan as well as others (the point cloud also had colour in the form of RGB values).

Once processed features can be identified with the naked eye very easily, however the images must be converted back to a vector format (such as .shp) through a process known as vectorization. The quality of the source LiDAR and the target of the intended extraction is key, as this will inform the minimum geographic cell sizing constraints for the data binning during the conversion. This is because the conversion cannot accurately create new data, only aggregate up meaning that LiDAR with 2-meter resolution for example cannot produce raster images with cell sizes of 2cm (technically the process will run).

Once identified based on its physical properties, environment features can be extracted to single lines of text in a database if required. Maintaining an understanding of positional accuracy and shape throughout. This process enabled the rapid and accurate identification of key features from the point cloud, which could be fed in a lightweight format into the production of the virtual environment. An alternative method to consider for future research would be the use of more advanced CV (Computer Vision) techniques to automatically pick out features based on a library of know images rather than defining physical constraints.

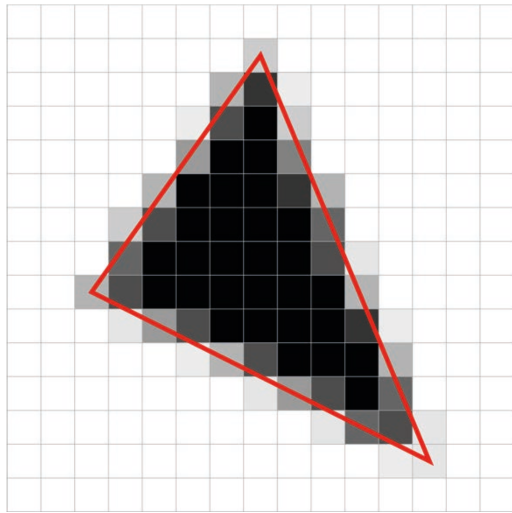


*Figure 6: Visual example of rasterization (source: de.wikipedia.org)*

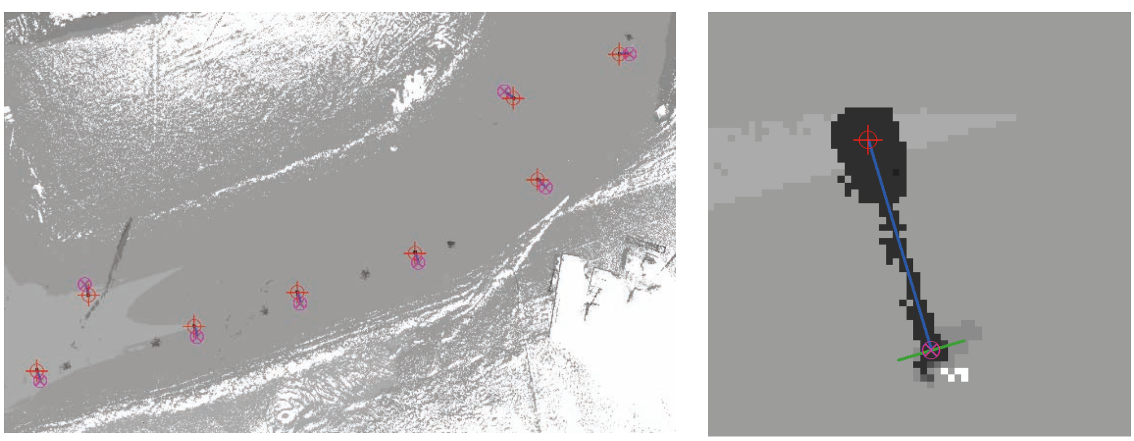


*Figure 7: Lamp post feature identified, rotation and positional information through vectorization and stored as a single line of text plotted*

In summary the workflow follows a continual trend of reducing data complexity while increasing the understanding of physical features within the data, while maintaining the maximum levels of accuracy confidence. The data stored within the Spatial Database can be connected to unity to rapidly place feature models allowing for the fast creation of spatially accurate virtual environments, with a high degree of visual fidelity.

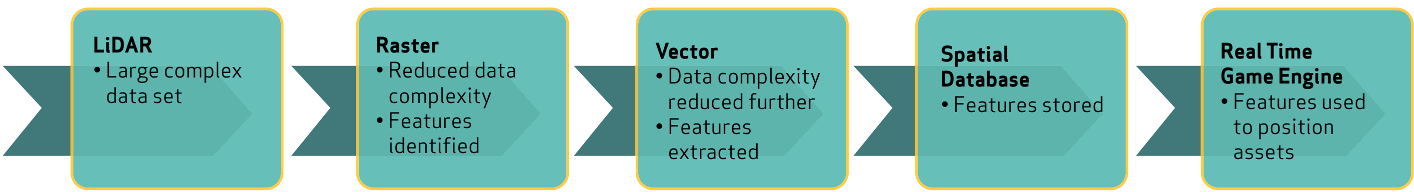



*Figure 8: Process diagram from Point Cloud to RTGE*

## 4.5 Data

The process of building the visualisation tool started with a need to gain rapid insights from raw datasets collected by our partners which conducted the physical trials with human drivers. These raw data sets eventually totalled hundreds of terra-bytes of data with broad and varying formats. Therefore, MatLab was used to process and the data into relevant formats.

## 4.6 Data Conversion and Processing

In this instance, MatLab was used to convert time (UTC), position (WGS84), orientation (roll, pitch, yaw), acceleration (forward, right, up), speed2D (m/s), brake pressure (%) and accelerator pressure (%) into useful data structures which were able to be mapped to systems and components residing within the Virtual World, within our overall Digital Twin.

Such data sets, including vehicle data and geodetic co-ordinate systems must first be converted into appropriate formats in order to correctly position and represent both assets and data within our engine of choice, Unity. Positional data was converted into WGS84 co-ordinates (Latitude, Longitude). Unity's world space co-ordinate system is left-handed Cartesian with the ground plane being assigned to X/Z with the y-axis providing altitude (Unreal for instance is right-handed with z-axis corresponding to altitude).

To achieve this, conversion from GPS (Global Positioning System) to UCS (Unity Co-ordinate System) was carried out. This conversion is based on the Spherical Mercator, EPSG:3857 algorithm, changing the co-ordinate projection from Longitude/Latitude to planar. This enables the localisation of a global position and offset received data from this point. This works effectively for small geographic regions but at a greater scale such as City scale or County scale, Unity is not immediately ready to render objects at such a distance from world centre. In order to work around this, it was decided to reset the origin at the point in which the focus area bridges over to an adjacent geographic tile, prompting a load and unload to occur. The Unity engine uses transform components to define an objects location, orientation and scale in world space. These contain Vector3 (position/scale) data structures which are inherently designed to ingest floats (as was the plugin for converting GPS – UCS). The use of float values within Unity introduced a reduction in positional accuracy within the Digital Twin. To mitigate against this as much as possible, a math library was imported to enable a Vector3 to receive double parameters, resulting in a significant increase in the confidence of the accuracy of converted data. This now provided us our x and z co-ordinates to define an objects position in Unity world space.

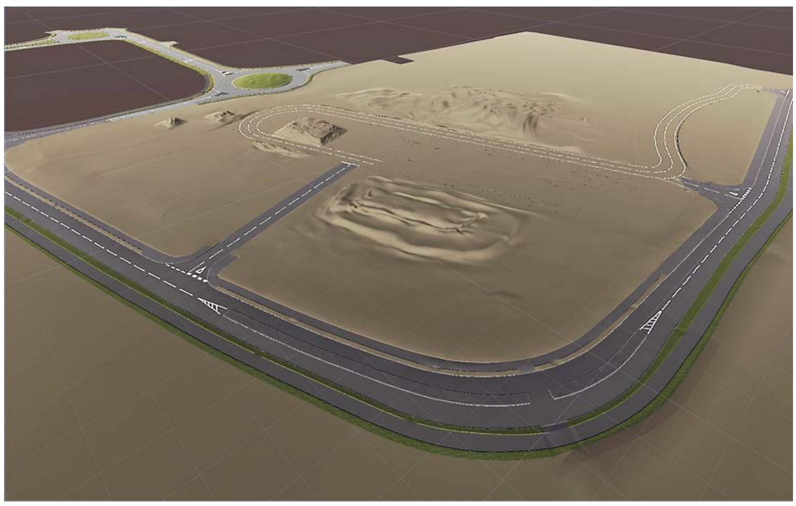


*Figure 9: Mueavi test track 3D geometry created from dense point cloud data collected by MK Surveys*

*Figure 10: This is the same as the environment above, inclusive of the positional traces of the main participant.*

## 4.7 User Interface prototyping and data integration

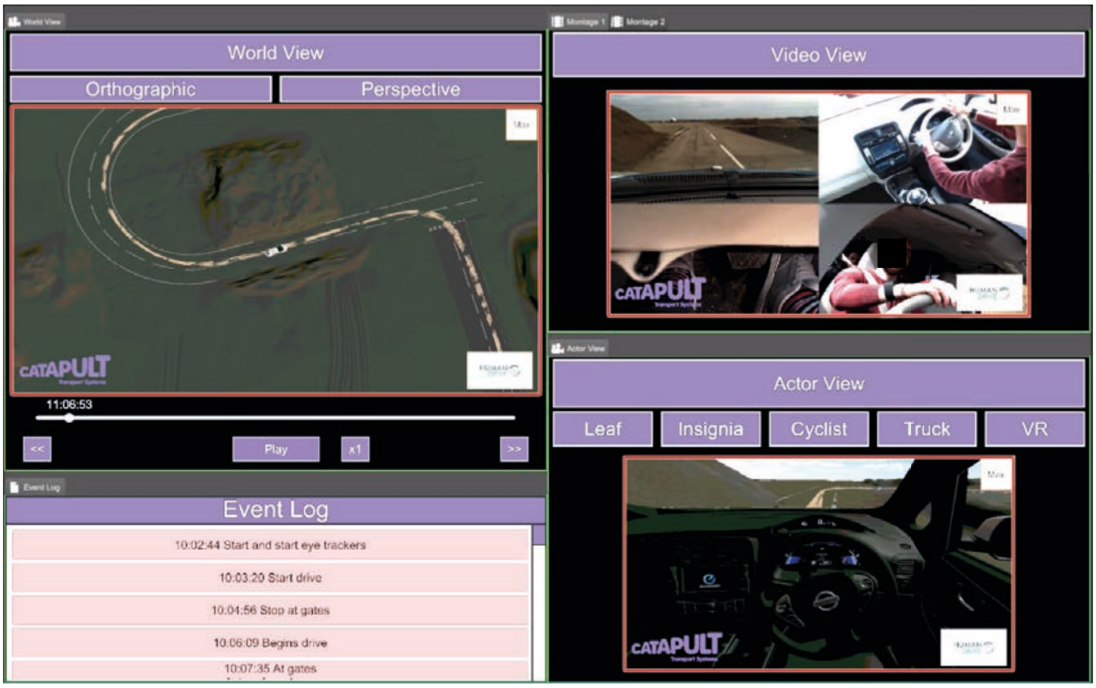



*Figure 11: The playback dashboard showing the data lining up with the geometry as well as video synchronised with the virtual actors movement and perspective views, this also corresponds with the 'world view' position indicating where it is relative to actors and assets.*


*Figure 12: Data and graphing panel displaying the entire trial dataset with the ability to increase the granularity of the current point in time 15 seconds before and after. The Markers allow the user to indicate what behaviour they have experienced at that time within the trial*

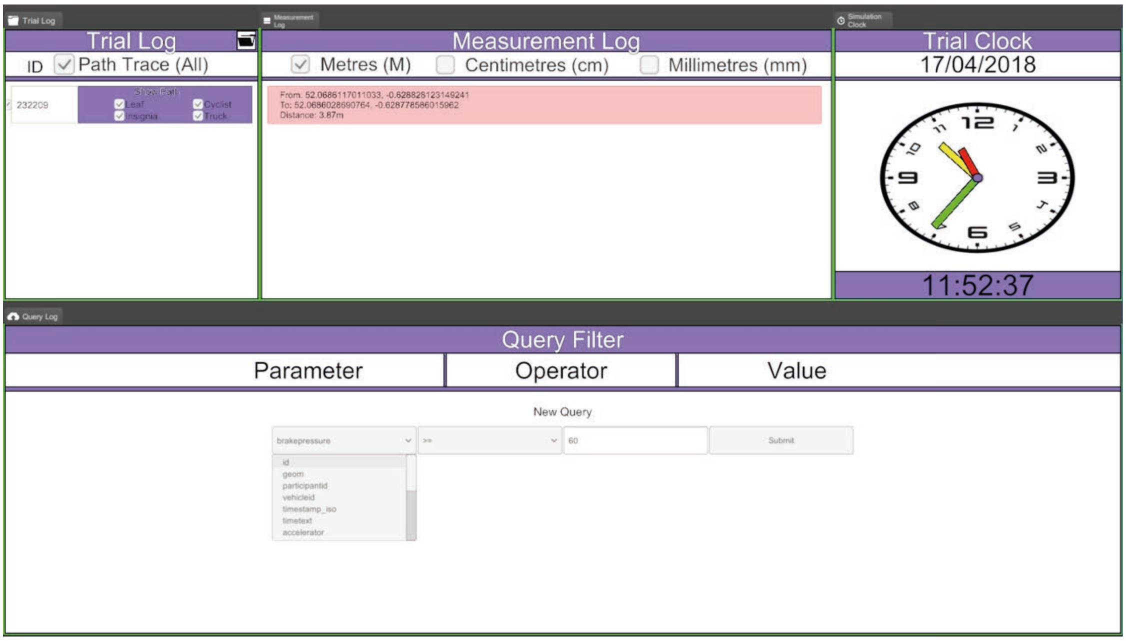



*Figure 13: Loader and query panel allowing the user to identify the date/time of the trial, measure distances at any point in the trial and refocus to key point of interest along the timeline.*

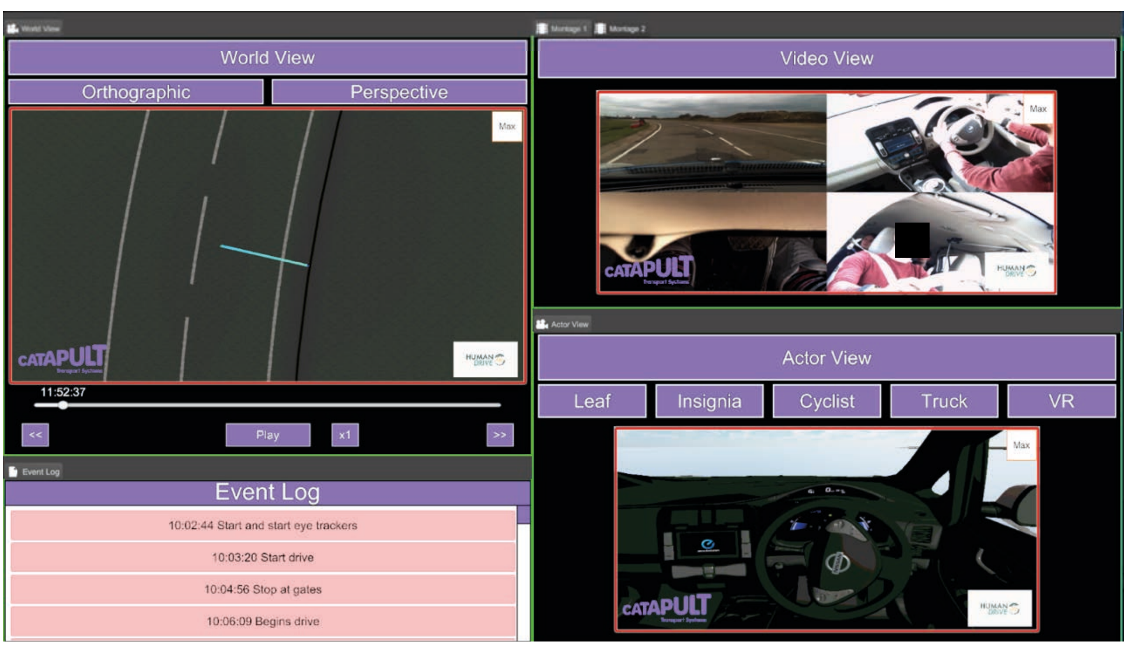



*Figure 14: Example of the focused measurement, linking back to the playback panel and the point in time/participant associated with that action.*

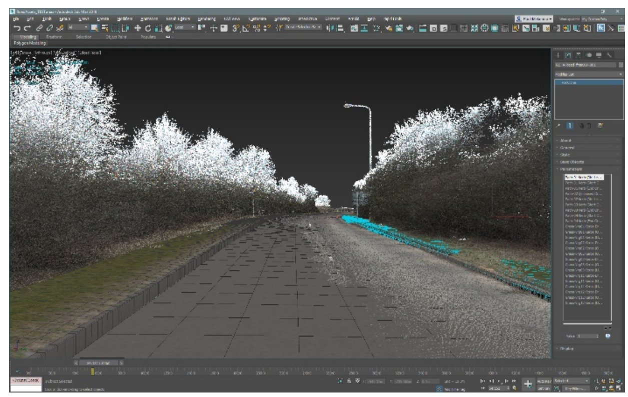
### 4.8 Environmental Conditions

Environmental weather conditions were beneficial to the analysis of driving behaviour, allowing us to gain even greater insights. This data was provided to us from the UK Met Office, via the closest relevant weather receiver throughout the duration of the entire trial programme. Examples of the data received includes weather condition description, rain precipitation, temperature and visibility. This data was extremely useful to us, allowing us to represent accurate weather conditions within our Digital Twin.

# 5 VIRTUAL ENVIRONMENT CREATION

## 5.1 Autodesk 3DS Max

Due to the compatibility of the cleaned-up point cloud, the TSC 3d Modelling team was able to be import the data into our 3d Modelling package of choice, Autodesk 3DS Max. Once within 3DS Max, a series of Splines were produced, based on/snapped to the Point Cloud which represent the centre of the road for the entirety of the road network (roads around Cranfield University) captured in the point cloud. This Spine, or Control Spline forms the basis of the Road Surface, Kerbs, Verges, foliage and nearby terrain features.



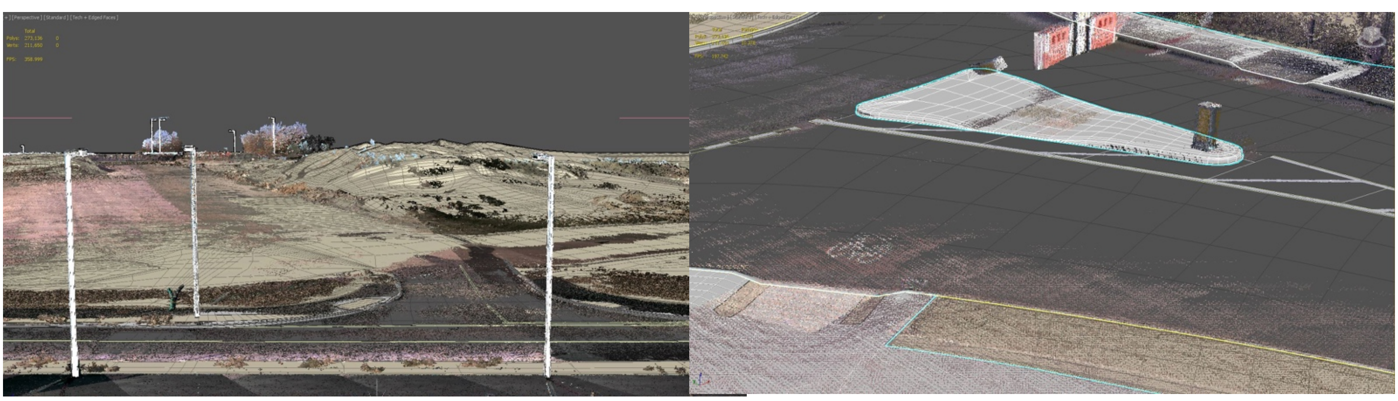


*Figure 15: Point cloud in 3DS Max*

## 5.2 Parametric Tools

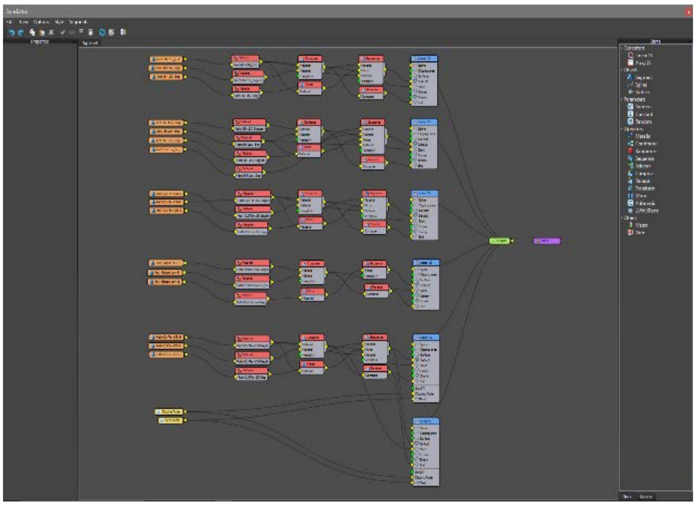


*Figure 16: 3DS max model tree*

The production time, editability and future expansion of the digital twin was of key importance to us.

In order to achieve this, it was decided to leverage the benefits of parametric design tools within the environment creation process. This was achieved using Rail Clone developed by iToo Software, a powerful artist-friendly parametric modelling plugin for 3Ds Max. Based on the use of Rail Clone, a 3d Asset Library was produced consisting of modular sections of the Cranfield environment.

This library is designed to efficiently 'snap together' using the Rail Clone system. These modular pieces are Low Polygon, UV Mapped and Textured ready for arraying via the rules-based system created using Rail Clone.

The relationship between the elements of this library are essentially designs to both manipulate and inform the design of complex virtual environment, geometries and structures. Through using Splines, derived from the processed Point Cloud data as a basis for Parametric Modelling, the result is not only an environment which is rapid to produce, but one that is extremely easy and quick to modify. Due to the live connection within Rail Clone inside of 3DS Max, Spline Point positions can be modified and moved whilst connected to the environment's geometry, controlled through the relationships managed by and created through Rail Clone. This makes alterations to elements such as road surface direction, height and camber possible within several mouse clicks as opposed to a lengthy and costly re modelling process.

## 5.3 Real Time 3D Engine

*Figure 17: Digital twin of MUEAVI*

Real-time rendering is a sub-field of computer graphics, focusing on the production and analysis of images in real time. The term can be applied to both 2d and 3d content, including Graphical User Interfaces (GUI), 3d models and 2d computer graphics.

Real-time graphics systems must render each image in less than 1/30th of a second or faster. Ray tracing is too slow for these systems; instead, they employ the technique of Z-buffer triangle rasterization. In this technique, every object is decomposed into individual primitives, usually triangles. Each triangle gets positioned, rotated and scaled on the screen, and rasterizer hardware (or a software emulator) generates pixels inside each triangle. These triangles are then decomposed into atomic units called fragments that are suitable for displaying on a display screen. The fragments are drawn on the screen using a colour that is computed in several steps. For example, a texture can be used to "paint" a triangle based on a stored image, and then shadow mapping can alter that triangle's colours based on line-of-sight to light sources.

In this instance, Unity was the chosen real time 3d engine due to its adaptability and our internal capability and expertise with Unity. Unity gives users the ability to create games in both 2d and 3d, and the engine offers a primary scripting API in C#, for both the Unity editor in the form of plugins, and games themselves, as well as drag and drop functionality.

For 3d games, Unity allows specification of texture compression, mipmaps, and resolution settings for each platform that the game engine supports, and provides support for bump mapping, reflection mapping, parallax mapping, screen space ambient occlusion (SSAO), dynamic shadows using shadow maps, render-to-texture and full-screen post-processing effects.

Unity was used to bring together, synchronise and host the data sets gathered from the user trials as well as a development environment for Virtual Twin assembly and User Interface development. Whereas unique 3d Assets are produced within 3DS Max, Unity was used to assemble these assets based upon the Vector Co-ordinates provided by our feature extraction tools. Not only does this save a vast amount of time in terms of Virtual Twin authoring but it also ensures that the result is quick to update, adaptable, dynamic and optimised in terms of file size footprint.

A major advantage of using a real time 3d engine such as Unity (or Unreal another RTGE) for this application is the technology focus on visual fidelity and physically based rendering. Both yield a great amount of opportunity for CAV testing in scenarios where realistic environments for both software and hardware-in-the-loop testing is of high importance. Modern engines such as Unity and Unreal, enable users to author highly accurate, physically based environments. This is inclusive of lighting, material properties and environmental conditions. Both RTGEs are a natural fit in digital twin production workflows due to their robust, adaptive and configurable nature.

## 5.4 User Interface development

A User Interface was subsequently developed within Unity to bring together the outputs from the trial data, data processing outputs and synchronisation along with the virtual twin of the real-world trial location. The combination of the data sets within an intuitive and easy to manipulate interface is designed to enable teams with varying expertise and skill sets to interrogate and cross-reference data in an objective, contextual and insightful manner. The scale, quantity and complexity of the user trial data sets are what drove the development of the front-end User Interface. Through presenting this information within a contextual, intuitive, geospatially accurate and accessible interface, the quality of the insights is far greater than the sum of each part. It was found that our ability to interpret and understand Objective Data when bringing together into one, easy to interpret and cross-reference place is exponentially greater than interrogating these data sets in a disconnected and out-of-context manner.

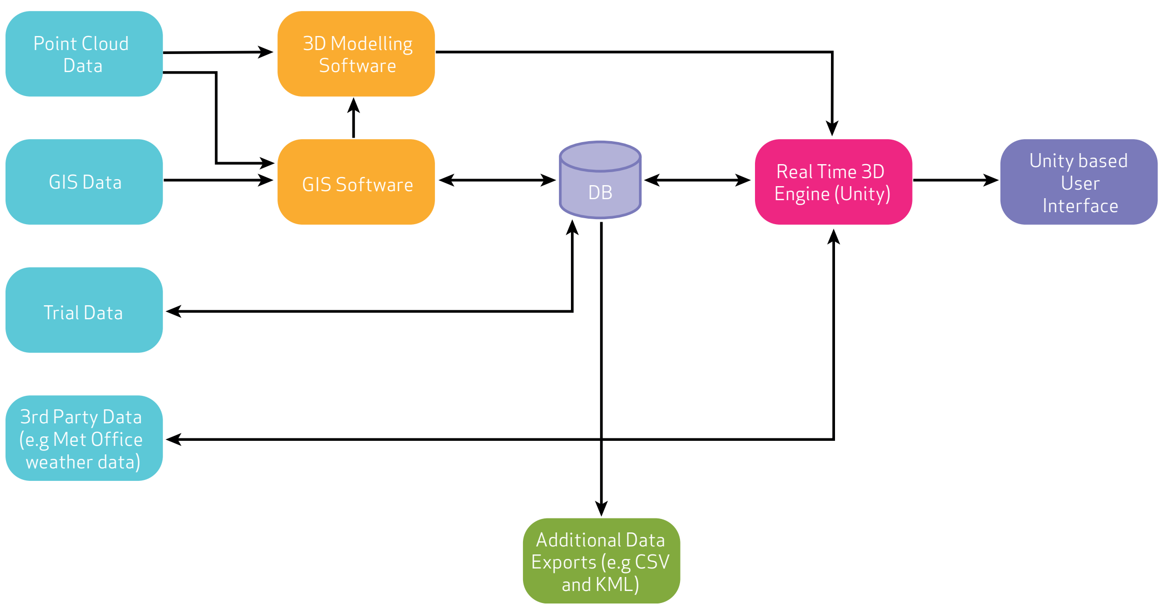



*Figure 18: Process diagram for raw data input to data visualisation and output*

The production of this digital twin required our teams to resolve several technical barriers including large scale complex virtual environment creation, continuity of geospatial positioning, data synchronisation, networking, the processing of massive point cloud files and ensuring the accessibility and usability of complex and varying data sets. The result of this work is an intuitive interface which provides users with an easy to interpret, synchronised and contextual data sets to enable greater understanding and insight from real-world user trials. In addition, the digital twin is designed for rapid modification and expansion using the workflow methods and techniques during the development phase. These methods however are not limited to this application, they can be employed across all types of digitisation of real-world environments during the production of digital twins.

# 6 CONCLUSIONS

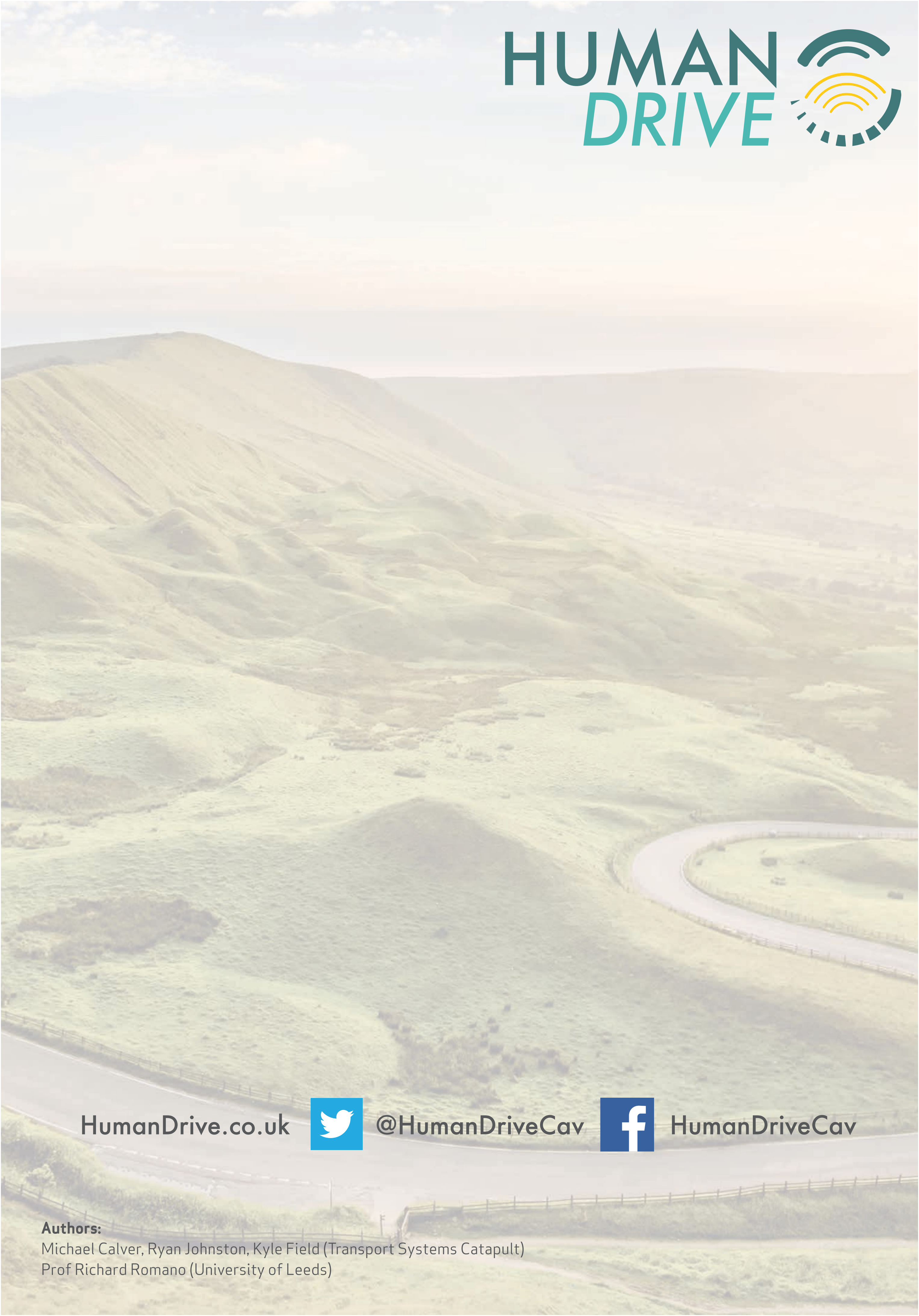
Digital twin technology has the potential to positively impact and benefit organisations cross-sector. It is predicted that by 2020, 30% of G2000 companies (https://www.digitalistmag.com/iot/2018/05/23/will-there-be-digital-twin-for-everything-everyone-06169041) will be using data from digital twins and IoT connected products to achieve product design, productivity and innovation success rates gain for up to 30%. The benefits and use cases of digital twins include but are not limited to the following areas:

- Virtual Prototyping
- Smart connected products
- Customer driven design
- Predictive models
- CAV development and testing
- Continuous data-driven optimisation

The use cases for digital twins vary in usage due to the potential adaptability to many applications using sensors, cognitive, analytics and simulation technology. It is suggested by Professor Mark Skilton who co-authored "The 4th Industrial Revolution" that digital twins will become the de-facto standard for many items that you purchase, from cars to living spaces. He continues to add that:

> **"It will represent new opportunities for companies, municipalities and governments to develop true smart cities and services based on a higher level of precision of location and experience."**

Digital twins will be a disruptor for numerous industries and are poised to radically change business models. Digital twins ultimately capture and leverage the power of emerging technology, IoT and data relating to people, products, spaces, places and change how organisations design, simulate, manufacture, perform, predict and respond.



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