THE FUTURE
OF TRANSPORT

PROJECT REPORT ACA105

Motorcade

Analysis toolkit for monitoring trials of zero emission vehicles

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Executive summary

The UK Government's climate change strategy has set ambitious targets to decarbonise transport. To support this the government has funded several programmes to develop new vehicle technologies and fuel/energy supply chains. However, to understand the performance of these new technologies there is a need for standardised tools that capture vehicle data and provide assessments of energy use that can be applied to compare energy consumption objectively, using standardised parameters to characterise the duty cycle.

Because the government's plan to decarbonise UK's transport system will make varied fuel fleets inevitable, it is also desirable that such a tool should provide a solution that is capable of monitoring different fuel types across fleets of vehicles. Fleet performance monitoring would collect and examine data such as fuel/energy consumption, operating hours, distances driven, payload, mechanical faults, and driver behaviour on fleets. These can be used to calculate performance indicators such as fuel economy, greenhouse gas emissions, vehicle utilisation and reliability and would serve as a valuable tool for evidence-based decision-making and strategic planning. This fleet performance monitoring tool has been the focus of the Motorcade project.

As part of an Innovate UK grant-funded project and TRL's Strategic Investment Programme (SIP), TRL has previously investigated how a toolkit to provide vehicle performance information (referred to as a Vehicle Analytics for Monitoring and Evaluation toolkit, VAME) could be developed. A number of analytical modules were proposed, tailored to specific vehicles and fuel technologies, but with limited comparative evaluation capability for fleets of vehicles. The Motorcade project has built on the knowledge and insights gained in the initial development of the VAME toolkit, consolidating its initial analytical equations and tools into a coherent framework, and testing this with a range of samples of real-world data.

To develop the toolkit, Motorcade has drawn on data provided in two projects undertaken in 2021-2022. These projects demonstrated the use of a hydrogen fuel cell bus and a prototype refrigerated truck (electric drivetrain fitted with a fuel cell), both providing telematics data on energy consumption. Through an iterative development process, the project has obtained a deep understanding of how to handle the telematics data, including granular data errors, inconsistencies, spikes, missing data, uneven granularity, sparsity, ambiguity in units of measurement, unrealistic data values, and disparate methods of capturing fuel utilisation. This understanding has been applied in the development of conditioning, processing and analysis tools that have been implemented within an Azure-based VAME toolkit.

The project has developed standardised metrics for reporting performance in the toolkit and reports these in a Power BI dashboard. The toolkit enables comparison of performance across a range fuel technologies and vehicle types on a common baseline. By applying data from both bus and truck demonstration trials, Motorcade has shown how the VAME toolkit can be applied to compare fuel, energy (excluding energy demand due to weather), duty cycle, emissions and cost across vehicles using electric and hydrogen technologies. Recommendations are made for a number of refinements that could further improve the capability of the toolkit.

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1 Introduction

1.1 Background

The UK Government's climate change strategy has set ambitious targets to decarbonise transport. The government has funded several demonstration programmes to support the development of the new vehicle technologies and fuel/energy supply chains that will be required to achieve these targets. For example, the Low Emission Bus Scheme (LEBS) (Ognissanto and Jones, 2022), Low Emission Freight and Logistics Trials (LEFT) (LowCVP and TRL, 2020), and the Helm-UK on-road trials of diesel HGV platooning (TRL, 2022), in all of which TRL played a key role.

The major challenge in real-world trials is accounting for confounding factors that affect a vehicle's energy and fuel consumption. Some of these factors are traffic conditions, environmental conditions, route characteristics, auxiliary system usage, payload, and driving behaviour. These make 'like-for-like' comparisons between trial vehicles and a standard (baseline) vehicle difficult. The LEFT and LEBS trials used coarse data like monthly fuelling records and focused on comparability between baseline and trial vehicles and consistency of operation over long periods. However, this limited the ability of the trials to draw statistically significant conclusions, especially on any technologies that had relatively small impacts on fuel consumption. In Helm-UK, in-vehicle telematics were used to provide highly granular measurements of vehicle speed, fuel consumption and other parameters. This enabled much more sophisticated statistical methods to be used to compare baseline vehicles and trial-runs, and even quite small changes in fuel consumption (a few percent) could be measured with statistical significance.

The experience gained in these projects highlighted the necessity for a standardised, automated tool for capturing data at a high sampling rate. This would enable accurate comparison of energy consumption, taking account of energy used by ancillaries (e.g. cab heating/cooling, and trailer refrigeration) and using standardised parameters, such as characteristic acceleration, aerodynamic speed, and kinetic intensity, to characterise the duty cycle.

As the government's plan to decarbonise UK's transport system will make varied fuel fleets inevitable, it is also desirable that such a tool should provide a solution that is capable of monitoring different fuel types across fleets of vehicles. Fleet performance monitoring would collect and examine data such as fuel/energy consumption, operating hours, distances driven, payload, mechanical faults, and driver behaviour on fleets. These can be used to calculate performance indicators such as fuel economy, greenhouse gas emissions, vehicle utilisation and reliability and would serve as a valuable tool for evidence-based decision-making and strategic planning. For example, fleet managers can use the information to make data-driven decisions, ensuring the selection of the most suitable vehicles and technologies for their specific operational needs. By optimising routes and loads and providing appropriate driver training, fleet performance monitoring contributes to the reduction of operating costs, maximisation of vehicle reliability, enhancement of safety, and the promotion of environmental sustainability. is required. This fleet performance monitoring tool has been the focus of the Motorcade project.

1.2 The Motorcade project

As part of an Innovate UK grant-funded project and TRL's Strategic Investment Programme (SIP), TRL has previously investigated how an outline toolkit to provide vehicle performance information (referred to as a Vehicle Analytics for Monitoring and Evaluation toolkit, VAME) could be developed for hydrogen fuel cell vehicles. The work developed a number of analytical modules, tailored to specific vehicles and fuel technologies, but had limited comparative evaluation capability for fleets of vehicles with varied fuels (petrol, diesel, electric, hydrogen fuel cell).

The Motorcade project builds on the knowledge and insights gained in the initial development of the VAME toolkit, consolidating its initial analytical equations and tools into a coherent framework, and testing this with a range of samples of real-world data. In particular the project has considered the following questions:

- What indicators are required for evaluating the performance of new vehicle technologies?
- How readily can data from vehicles using different fuels and drive trains be compared? E.g. diesel vs hydrogen fuel cell.
- What sensors and data are available in zero emission vehicles?
- What methods can be used to characterise duty cycles and enable like-for-like comparison to be made?
- What processing is required to enable the proposed analysis to be applied to real-world data to achieve?
- What level of data quality/ error rates can be expected in real-world telematics data and how can that be mitigated?
- Can standardised drive cycle parameters be reliably calculated for vehicles in real-world operation?
- To what extent would a VAME toolkit need to be customised to individual vehicles if used in future trials of zero emission vehicles?
- What conclusions can be drawn about the minimum sampling and data-handling requirements that would be required for a large-scale fleet trial?

Note: Previous trials, such as LEFT and LEBS involved a range of vehicle technologies and drivetrains, such as diesel-hybrids and CNG. Given government targets for zero emission vehicles it is expected that the focus of future trials will be on electric and hydrogen fuel cell vehicles. Therefore Motorcade has focused on these drivetrains. However, in most trials it will be necessary to consider a diesel baseline vehicle as a comparison for zero emission trial vehicles.

1.3 Acknowledgement

Motorcade has tested each module of the VAME toolkit (during the development programme) using samples of data from two vehicles involved in the previous Innovate UK project (a hydrogen fuel cell bus provided by Caetano and a prototype fuel cell truck from

Electra). We are grateful for the assistance these companies have provided to this project. It is important to note that the subject vehicles were not designed for scientific testing, and hence were not equipped with the full range of sensors that would be desirable for such tests. Nonetheless, the samples of data provided enabled the toolkit to be developed, and its performance investigated, using real-world data. The data from these vehicles is presented for the purpose of demonstrating the functionality of the toolkit and should not be regarded as representative indicators of their performance.

1.4 Structure of this report

This report is structured as follows:

- **Section 2** discusses the requirements for a vehicle analytical monitoring tool - the performance indicators, vehicle technologies, analysis techniques and data requirements. It concludes with an overview of the requirements for the VAME toolkit.
- **Section 3** describes the projects that were used as data sources for Motorcade.
- **Section 4** discusses the tasks undertaken and methods used to develop the toolkit and the analytics pipeline.
- **Section 5** provides examples of the outcomes of the analysis of the test data, demonstrating the capabilities of the analytics pipeline.
- **Section 6** discusses the lessons learned in the development.
- **Section 7** presents conclusions from the work and recommendations for future development.

2 The requirements for a vehicle monitoring toolkit

2.1 Performance indicators for monitoring and evaluation

To define the requirements for a monitoring toolkit is it first necessary to understand what data and indicators will be used, whether for a trial or for ongoing performance monitoring. The requirements are likely to be determined on a project-by-project basis, but would be expected to include key indicators such as:

- Fuel/energy consumption, usually expressed as a distance-based unit such as litres per 100 km for diesel fuelled vehicles, or kWh per 100 km for an EV. However, they can also be related to transport work done, for example as kWh per passenger km, or per tonne km. It is important to be able to separate energy used for traction from ancillary loads, such as heating and goods refrigeration.
- Greenhouse gas emissions, usually as 'well to wheel' emissions of $CO_{2,}$ should take account of emissions arising from production and transport, as well as direct from the vehicle. These are calculated from the fuel consumption data, using appropriate conversion factors for the fuel or electricity supply under consideration.
- Operational indicators, such as distance/time in service; trip lengths and times; terrain (altitude climbed), vehicle loading parameters such as tonne-km or passenger-km carried; average speeds etc. This information is required by operators to help optimise vehicle utilisation, but it is also needed to characterise the duty cycle of a vehicle to interpret energy and environmental indicators, to make comparison between trial and baseline vehicles, and to draw conclusions about their application to similar types of operation more generally.
- Reliability indicators, such as vehicle availability, time between failures, average time to repair etc, which are helpful for operators to manage their fleets effectively and to understand the wider operational implications of introducing new technologies.
- Driver performance indicators - such as harsh braking and acceleration, and average energy consumption achieved by individual drivers - can be collected to support performance management and training. This is widely undertaken by commercial fleet operators, but involves handling of sensitive personal information, so has not been included in toolkit development to date. Such indicators can also be used for safety monitoring purposes.

As will be discussed in greater detail later, it is desirable to be able to characterise the duty cycle of a particular vehicle trip using standardised parameters. This makes it easier to ensure that trials are undertaken on a like-for-like basis and enables comparison of a vehicle's performance with the results obtained from standard track and laboratory tests. It is also desirable to collect information on the fuel or electricity supply pathway used. This is particularly important for hydrogen as there is a wide difference in the 'well to tank' (WTT) carbon intensity of fuel obtained from different manufacturing processes. WTT emissions can be calculated using 'standard' emission factors (e.g. from BEIS or from Zemo Partnership) to enable like for like comparisons of technologies, and using project-specific factors that may more robustly reflect the actual energy pathway used in a particular fleet.

2.2 Overview of zero emission vehicle technologies

It is important to consider the drivetrain architecture and energy flows between components to specify data necessary for vehicle's monitoring system. Hydrogen fuel cell and battery electric vehicles share electric drivetrains, and electrically powered heating and ancillary loads. Internal combustion vehicles draw power from the drivetrain for ancillary functions.

Battery electric vehicles (Figure 1) use an on-board battery as the main source of energy to provide traction via an electric motor. Electricity from the electricity grid is used to recharge the battery. By using the motors 'in reverse' as generators, electric vehicels are also able to recoup otherwise wasted braking energy through regenerative braking - improving efficiency.

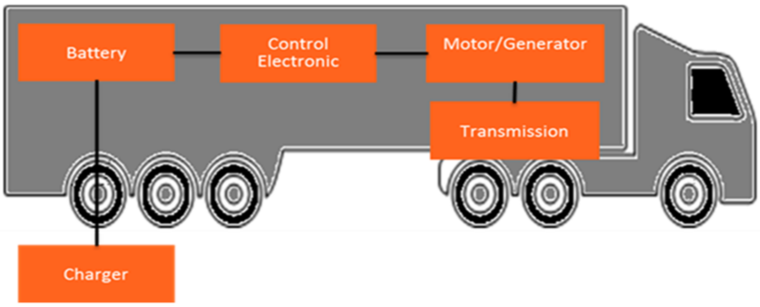

Figure 1: Battery electric vehicle simplified schematic

The electric drive train of a fuel cell electric vehicle (Figure 2) is similar to that of a conventional battery electric vehicle. It includes a 'buffer' battery that stores energy during regenerative braking, or at times when there is low demand for traction energy, and then supplies it when additional power is required. The fuel cell is supplied from tanks containing compressed hydrogen and is controlled to operate steadily at an optimal power level. The buffer battery manages short term variations in demand. In principle a vehicle could rely on the electricity produced by the fuel cell only. However, if a larger internal battery is fitted then fuel-cell vehicles can also be used as plug-in hybrids, taking energy from an external charger or from hydrogen, benefitting from the lower cost of electricity while having the advantage of the greater maximum range provided by the fuel cell.

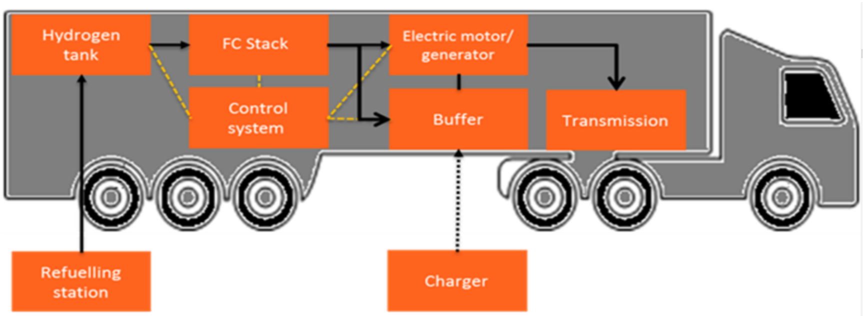

Figure 2: Hydrogen fuel cell vehicle, simplified schematic

Because of the complexity of the energy flows to and from the battery within battery electric or fuel cell vehicles (Figure 3), it is necessary to measure power flows at several different points. Battery State of Charge (SoC) must also be measured to capture the full range of information required to monitor the energy used by the vehicle over a trip. However, measurement of hydrogen consumption is complicated due to unreliable flow meters for hydrogen. For the vehicles that TRL has worked with to date the hydrogen consumption has been measured from the change of the mass of hydrogen in the tanks, calculated from the temperature and pressure measurements at the tanks.

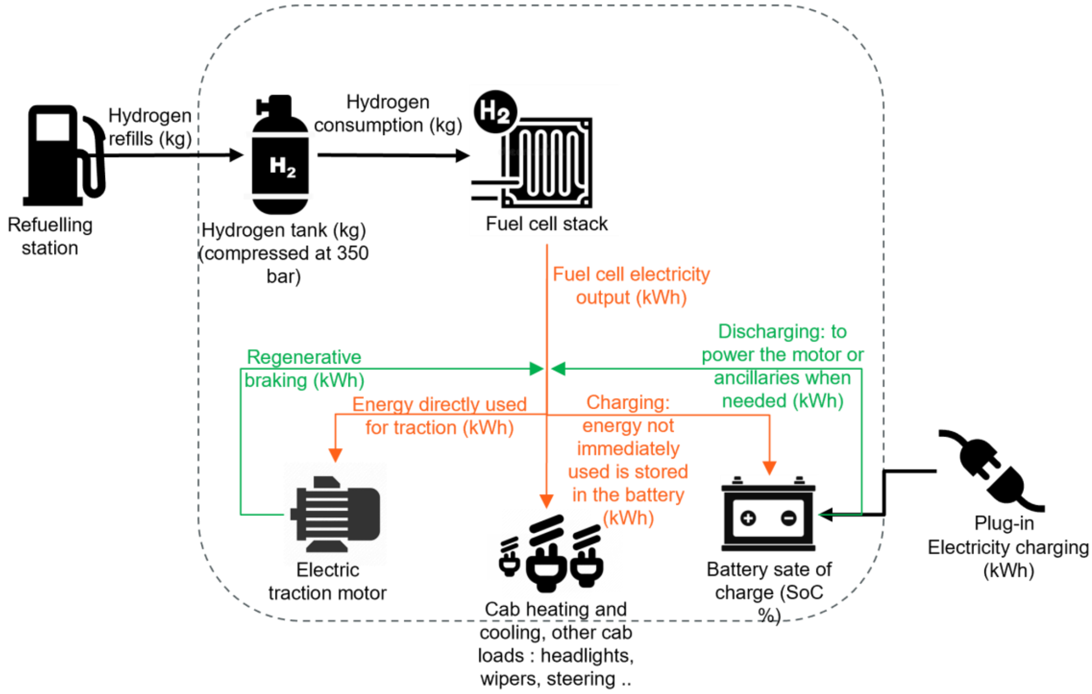

Figure 3: Energy flows within a plug-in hybrid hydrogen fuel cell bus

2.3 Summary of data requirements for the toolkit

To enable a toolkit to calculate the indicators described in this section requires data to be collected from a range of different on-board sensors, by means of on-board telematics. The main requirements are:

- Fuel and energy flows throughout system- including both traction and ancillary loads
- Vehicle and engine status
- Fuel tank and battery State of Charge (SoC)
- GPS position, altitude, time, speed
- Driver controls- harsh braking etc
- Loaded weight (goods vehicles)
- Environment- internal and external temperatures (to assess heating and cooling loads)

Ideally, on-board measurements of fuel and electricity consumption should be supplemented by data from external charging/ refueller infrastructure, for error checking and to identify leakage/ losses. As discussed previously, for robust duty cycle characterisation, a minimum sample rate of 1 Hz is required for speed and altitude (using GPS). Other parameters may not be measurable at that frequency but need to be quantified over a trip. The vehicle analysis system therefore needs to be able to handle data at a variety of sampling rates to provide the required indicators at a 'per trip' level.

Separately from the real-time monitoring, it is also necessary to obtain key parameters relating to the specification of the vehicle, so that data can be interpreted appropriately and, where required, theoretical fuel/ energy consumption be calculated.

2.4 Summary of analysis and reporting requirements for the toolkit

Having identified the nature of the data that needs to be collected from vehicles, and the output indicators required for monitoring, we can hence identify the data analysis tasks required of a performance monitoring (VAME) toolkit:

- Capturing real time data for fuel/ energy consumption and vehicle operation, directly from telematics.
- Data transfer, cleaning, and filtering, ensuring analytic quality (preferably automated).
- Calculating descriptive statistics of trips undertaken, including total fuel/energy used; and calculating resulting greenhouse gas emissions.
- Characterisation of drive cycles, so that real-world results can be compared on a like-for-like basis and extrapolated to specific use-cases.
- Analysis of energy consumption by ancillaries, including analysis of heating/cooling demand by external temperature.
- Reporting standardised indicators, within a template to streamline reporting, allowing for periodic reporting at different levels over different time periods.
- Providing suitable data storage and retrieval, to allow for quality checking and audit processes, and to enable selected data to be exported for bespoke statistical analysis.

3 Data Sources for the Motorcade project

The Motorcade project has used data provided by two demonstration projects undertaken in 2021-2022 (supported by Innovate UK) to develop the VAME toolkit. These demonstration projects were not scientific trials of vehicle performance. However, the data collected was of value for the development of the toolkit, extending its capability to hydrogen fuel cell plug-in hybrids, and providing data collected in on-road conditions.

3.1 Teeside Multimodal Ecosystem

The Teesside Multimodal Ecosystem project (Element Energy, Toyota, Wright bus, Caetano and TRL) was a demonstration of hydrogen fuel cell vehicles in the Teesside area. The hydrogen was produced by electrolysis using renewable electricity and delivered by truck to the refueller. Refuelling was undertaken by Element 2 at the Stagecoach Stockton-On-Tees Depot. The bus featured a PEM fuel cell with a power rating of 60 kW, hydrogen fuel tank capacity of 38 kg and a 44 kWh battery. It had a capacity for up to 65 passengers. The bus was driven on a range of routes, including town centre and inter-urban operations, covering a range of different drive cycles, between January 2022 and March 2022.

The demonstration trips were not representative of typical bus operation. There were many short trips between locations and idling time, and generally low daily mileage. It was not the purpose of the demonstration to undertake representative monitoring of performance, and trips were not specified for this purpose. Furthermore, the vehicle was an older model used for demonstration purposes, with a performance and specification that do not reflect vehicles currently available from this manufacturer[1]. However, the project yielded three key outcomes: insights into FCEV integration and energy flow, the identification of data requirements for VAME toolkit development, and outputs from an initial toolkit to inform larger-scale trials and commercial deployments of hydrogen technology.

3.2 The Road to Hydrogen

The Road to hydrogen project (Element Energy, Electra, Durham University and TRL) demonstrated the use of hydrogen fuel cells in a prototype 19 tonne refrigerated truck. The vehicle was a conversion by Electra of an existing chassis, using an existing electric drivetrain technology fitted with a 43 kW fuel cell and four compressed hydrogen tanks (total capacity of 19 kg at 350 bar[2]). The Electra vehicle is intended to be used as a plug-in hybrid, having a sufficiently large (225 kWh) battery to operate on electrical power for up to 210 km. TRL worked with Electra to gather information on the vehicle, its specification and the data that would be collected from it. The vehicle was not introduced into commercial operation during the project. However, Electra was willing to continue to cooperate with TRL in the further development of the VAME toolkit, which enabled us to continue the testing and development of the toolkit through the Motorcade project.

[1] https://caetanobus.pt/product/h2-city-gold/

[2] https://www.electracommercialvehicles.com/hydrogen/

4 Development of the toolkit

An illustrative summary of the stages in the "analytics pipeline" for the toolkit (using the telematics data to understand vehicle performance) is shown in Figure 4. These are summarised in the following paragraphs and explained in greater detail in the following sections.

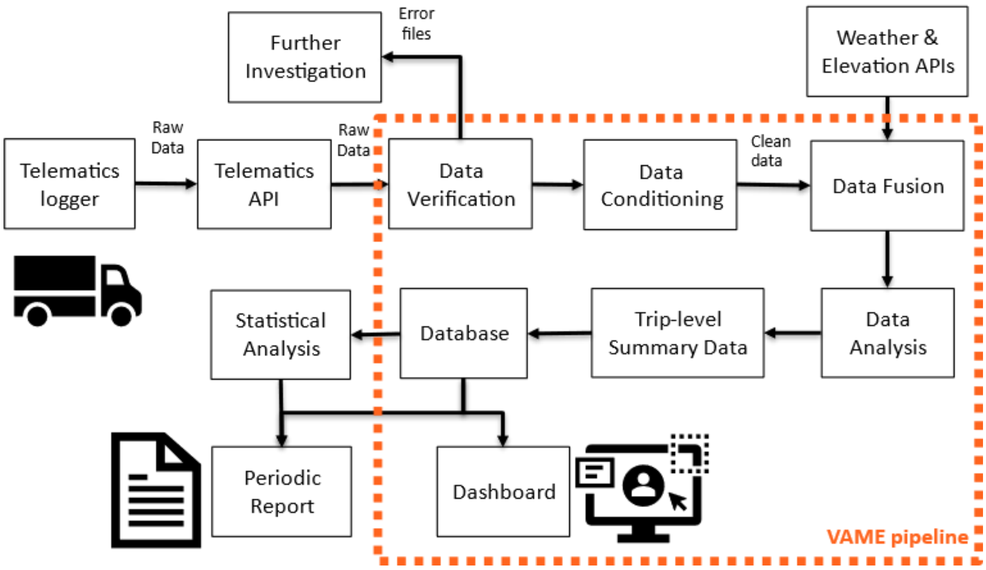

Figure 4: Conceptual diagram of the data collection and analysis pipeline

The key stages in the pipeline are:

- **Data Acquisition**: the process of getting the data from the vehicle telematics, either directly via a mobile data connection to each vehicle or using an online service from a third-party telematics provider.
- **Data conditioning**: Once files have passed through the data verification phase, files that do not raise any errors proceed to the data conditioning stage. This stage carries out any needed data conversion and, in some instances, fills in missing data where there are periodic signal dropouts. Synchronisation of data fields by time also occurs.
- **Data fusion**: Because elevation data from telematics loggers can be unreliable, especially in built-up areas where tall buildings affect the resolution and accuracy of the measured elevation, an Elevation API that uses the GPS grid coordinates was used to provide altitude measurements. To account for external factors such as weather and topography, additional data sources can be retrieved using a weather API.
- **Data analysis**: Conditioned data signals are used to calculate the metrics of interest as discussed previously, for example hydrogen consumption, energy input, drivetrain energy use, auxiliary systems energy use, time driven and journey time, and drive cycle parameters.

The following sections describe these components of the pipeline in more detail and how they were developed in Motorcade for application in the toolkit.

4.1 Data acquisition

4.1.1 Methods of data collection

Data was collected using the in-vehicle telematics[3] system and downloaded by TRL from the online API[4] portal, for the development of the toolkit. Key features of the data collection included:

- For buses, data was collected using the ViriCiti in-vehicle telematics system and downloaded by TRL from the ViriCiti online portal. Measurements were sampled at a maximum frequency of ten readings per second.
- For the HGVs the vehicle telematics data was collected through an API request to an online portal provided by Codesmith Technology for Electra. Measurements were sampled at a maximum frequency of one reading per second.
- Many parameters were monitored by the telematics system to support the calculation of the performance indicators discussed in Section 2.1, with the most important parameters being:
    - Distance driven by the vehicle with time stamp (tachograph and GPS)
    - Latitude, longitude, and altitude (by GPS)
    - Speed (measured both by odometer and GPS)
    - Hydrogen (fuel) consumed (either pre calculated or computed using pressure and temperature values in the four tanks)
    - Energy produced by the fuel cell
    - Energy used by the traction motors
    - Regenerative braking energy
    - Energy used for heating and other ancillaries
    - Vehicle battery State-of-Charge (SoC)
    - Vehicle load (either as passenger numbers or load)
    - External temperature
    - Status indicators: ignition, brake, fuel cell, plug-in charging connector
- Data density is affected by signal capture by the telematics system, rendering it very large missing data.

In addition to fuel consumption data reported by the vehicle telematics, a refuelling log was also provided by Element2, the fuel provider. This provided information on the total amount of hydrogen supplied to the vehicle, enabling a comparison to be made between fuel

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[3] Vehicle telematics, a system that collects, transmit, and analyses data from vehicles, providing valuable insights into their performance, location, and driver behaviour.

[4] API portal, a centralized platform that provides developers and stakeholders with the ability to access and integrate data. API integration provided a standardised and streamlined way to access data from multiple vehicles. It simplified the integration process and allowed scalability and consistency across different vehicles.

consumption reported by the vehicle and the total fuel supplied as reported by the refuelling infrastructure. The Electra truck was a prototype vehicle and so its telematics capabilities were not specified for the purpose of conducting longer term monitoring for in-service trials. Much of the data provided by the telematics was primarily for diagnostic purposes.

4.2 Data conditioning

4.2.1 Data limitations

Although the data provided from the on-board telematics was generally consistent and reliable, there were several challenges:

- **API**: The practicality and robustness of the data download can be affected by the API structure. The API tools may facilitate per journey download, or only monthly data, or they may/may not allow the selection of parameters, or require complex navigation through the portal, or require code scripts, and offer limited ability to manage the sampling rates etc. For example:
    - The Codesmith API allowed users to only request 10,000 rows of data at a time. Loops were required to extract data covering longer periods. This added a layer of complexity and additional development time. Although this issue may be specific to the Electra API, it is worth noting when considering the access/processing needs for future data providers.
    - Sometimes gaps appeared in the timeline requested by the API. This problem occurred mostly when requesting times longer than 10,000 seconds (e.g. a day), and attempting to loop through the timeframe. There was no discernible reason for this loss of data. The issue was overcome by requesting data 1 hour at a time and including additional checks at the end of the request to remove all duplicate values that were extracted.
- **Data interpretation**: There was some ambiguity associated with the data downloaded from the APIs. For example:
    - **Nomenclature:** E.g._source.processedData.gnss_imu.AccelerationX, _source.processedData.Hydrogen_Tpdo03.PowerCurrentAct, _source.processedData.Hydrogen_Tank_3_4.Tank3Temp, does not provide a clear understanding of the content of these parameters.
    - **Definitions:** E.g. “Hydrogen while in service (kg)” and “Hydrogen used while not in service (kg)” appear clear but are still obscure as ‘in service’ is not a standard term that has universally understood definition.
    - **Repeated parameters**: Especially for time, GPS and odometer readings like _source.location.lat and _source.processedData.gnss_pos.Latitude. These cast confusion over the most appropriate parameters to choose for the task.
    - **Ambiguous units:** Neither the parameter headings or the API source provided the measurement units of speed, distance, temperature, vehicle load etc.

- **Data sparsity/missing data**: The data from vehicles provided in the demonstration projects (Section 3), was very sparse – in that there was a high percentage of data missing in comparison with that expected, given the sampling rate. This provided the largest bottleneck and impact on the performance analysis. E.g. in an example data set acquired from Virticity API the parameter 'Energy charged (kWh)' had 65% missing, 'Energy recuperated (kWh)' had 68%, and 'BTMS Status1 - BTMS Temperature In (°C)' had 70% missing data. There were examples where location data (GPS longitude, latitude, and altitude of the vehicle's position) were partially recorded or not captured at all. Potential approaches to reduce this problem include:
    - **At data generation:** to reduce the risk of missing data:
        - Deploy more complete/appropriate sensors for crucial data, for example sensors to monitor power flow to/from traction motors, from ancillaries etc, or to deploy sensors for hydrogen (fuel) tanks to measure fuel consumption directly, rather than depending on pressure and temperature signals.
        - Reduce comms/connectivity issues by deploying multiple network options (e.g. cellular, satellite) or signal boosters. Also, to monitor communication errors and rectify them.
        - Reduce the effect of intermittent power supplies by installing backup power sources.
        - Reduce the risk of failure of hardware by carrying out regular maintenance on the telematics hardware.
        - Ensure all relevant features are activated and functioning (and not disabled).
    - **After data collection:** In post processing (see Section 4.2.2):
        - Data selection criteria can be set to define thresholds for overall data density or number of data points to accept or reject downloaded data.
        - Data aggregation techniques can be applied to fill in gaps and interpolate between data appoints.
- **Data validation**: The data provided by the telematics included erroneous values, inconsistently recorded signals, missing time stamps, inconsistent units of measurement. The most affected parameters were the altitude measurements, the hydrogen consumption and the external temperature. Various checks needed to be carried out to ensure the integrity and reliability These are discussed in more detail in Section 4.2.2.

4.2.2 Data conditioning

The Motorcade VAME toolkit developed a number of data conditioning steps. Some of these arose from the limitations of the telematics data discussed above:

- **Data selection criteria**: These methods were implemented to select the records for analysis.
    - **Size**: For daily scheduled download, the file size was set to identify files containing high levels of data. Example, if the file size was less than 25 KB, the file was assumed to be poor/have missing data/from a short run etc, and was discarded.
    - **Length:** An aggregated distance was again chosen to secure files containing an adequate amount of data If total distance for the downloaded record was less than 1 km, it was discarded as an idle day.
- **Data validation checks**:
    - **Time Sequencing Checks**: These verified that the data timestamps followed a logical order and time intervals between data points were reasonable. Any data gaps or irregularities in the time series were corrected by adding a few rows corresponding to the missing time stamps.
    - **Duplicate detection**: All values corresponding to a duplicate timestamp were averaged.
    - **Data Range Checks**: These verified that all data values fell within acceptable ranges. E.g. an acceptable (believable) temperature range for the environment and battery. Erroneous values were replaced with NAN value.
    - **Geospatial Validation**: GPS coordinates were validated to ensure that vehicle positions were represented correctly. Any abnormal coordinates that suggested distance jumps in one time interval were replaced with NAN value.
    - **Consistency Checks**: Ensure that related data fields are consistent with each other. For instance, fuel and the SoC decrease with time as distance increases, with no change in distance and near zero speeds for idling periods, etc. These relationships were defined and visualised using plots.
    - **Data unit conversions:** All parameters were conditioned to match predetermined units (metric system).
    - **Data Smoothing**: Smoothing techniques were developed to reduce noise and improve the accuracy, especially for measurements prone to fluctuations (e.g. speed, altitude) The Savitzky Golay filter was used to reduce noise.
    - **User defined rules**: The acceleration/ deceleration per time interval was computed to identify speeds and distances corresponding to values that are not possible. Example, the permissible acceleration for buses and HGVs was kept to less than and equal to 1 m/s^2 and the permissible deceleration limit was less than and equal to 0.88 m/s^2.
    - **Data Interpolation technique**: Interpolation was used to fill in missing data points where there were data gaps.
    - **Adding data columns**: Depending on the needs of the processing, some data was pre-processed into other data. For example, latitude and longitude were converted to northing/eastings, fuel consumed from litres or kgs to kWh.

Other parameters were derived from those present in the dataset. E.g. acceleration from speed, harsh-braking, and acceleration events from acceleration, etc.

- **Validation using additional data**: Refuelling records were used to validate the fuel consumption calculated from the telematics data. Distance and speed calculated using GPS coordinates were validated against tachograph data. This build confidence in our approach and formulas.
- **Validation from data providers**: Caetano reported that the ancillary energy consumption data for Hydrogen buses were not accurate. The values were included for completeness, to demonstrate the analysis methodology, but should be regarded as illustrative.

4.3 Data analysis

4.3.1 Calculation of hydrogen consumption

While it is relatively straightforward to use a flowmeter to measure diesel consumption or Compressed Natural Gas (CNG) in an internal combustion engine vehicle, reliable hydrogen flow meters are harder to construct and hence expensive, especially for the comparatively low flow rate found in fuel cell vehicles. As noted above, the hydrogen fuel cell vehicles that TRL has worked with have all measured fuel consumption by calculating the mass of hydrogen remaining in the tank(s) from measured temperature and pressure. For one of the vehicles, the calculations were performed within the vehicle, so that the mass of hydrogen consumed is reported within the telematics data. However, the other vehicle provided the outputs from the individual temperature and pressure sensors, so that the fuel consumption had to be calculated within the VAME pipeline. This required the development of a module for calculating hydrogen mass from temperature and pressure measurements at the tanks. Although this would not be required for all vehicles, there is an advantage in having the capability for working with raw data, as backup and for error checking, even where the telematics system would normally calculate hydrogen consumption itself.

In the hydrogen truck the tank temperature was measured using a thermistor (whose electrical resistance falls with temperature) connected as a potential divider with a 10 kohm series resistor (R_{bias})and supplied with a stable 5V bias voltage (V_{bias}) Figure 5. The telematics system reports the potential difference across the thermistor (V_{sensor}) in mV. The resistance of the thermistor ($R_{thermistor}$) can therefore be calculated using the standard potential divider equation.

$$R_{thermistor} = (V_{sensor} \times R_{bias})/(V_{bias} - V_{sensor}) \qquad [1]$$

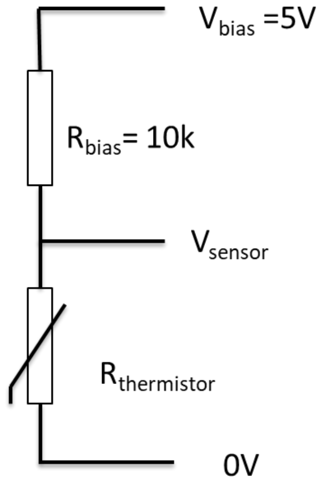

Figure 5: Connection configuration of the thermistor

A calibration table for the thermistor was provided that give values for the thermistor resistance at a range of temperatures in 5°C intervals (Figure 6). This table was used to produce a calibration curve. It is important to note that the curve was non-linear in the temperature range of greatest interest. This made the resistance to temperature conversion sensitive to errors in fitting of the calibration curve. Ideally a more precise calibration would be undertaken using much smaller temperature intervals.

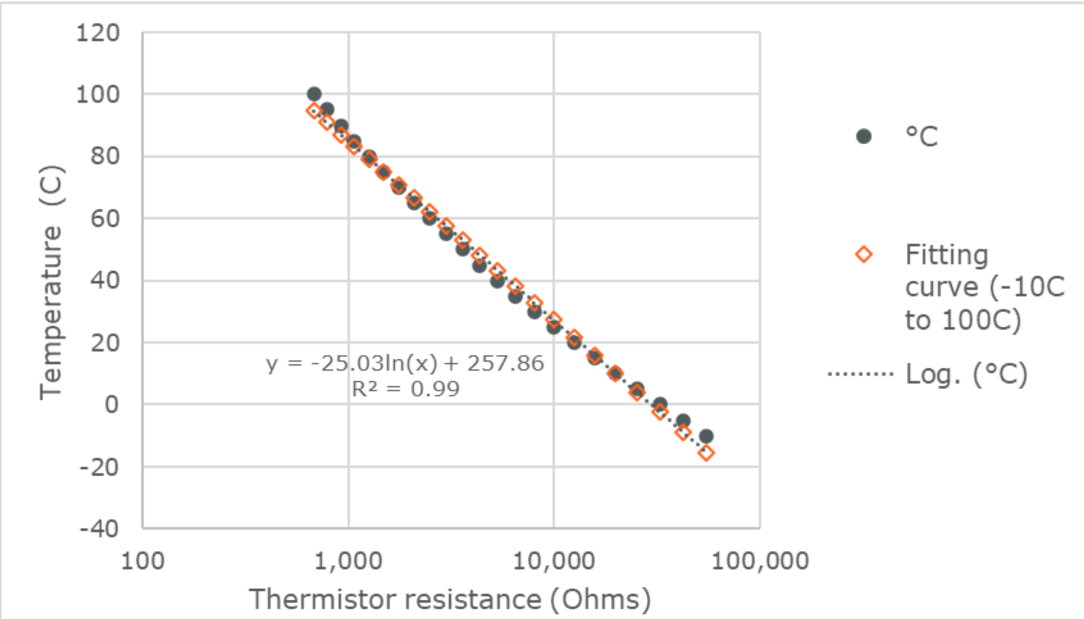

Figure 6: Temp vs resistance thermistor calibration curve

The pressure sensor field in the telematics data reports tank pressure in units of Bar x10. This measurement, together with the calculated temperature can be used to calculate the hydrogen mass in the tank. The ideal gas equation:

$$PV=nRT \qquad [2]$$

can be used to estimate the mass of hydrogen for a given volume, pressure and temperature. However, more accurate results can be obtained using methods that take account of hydrogen's behaviour as a real gas, for example using compressibility factor equation (Lemmon *et al.*, 2008):

$$Z(p,T) = \frac{p}{\rho RT} = 1 + \sum_{i=1}^{9} a_i \left(\frac{100\ K}{T}\right)^{b_i} \left(\frac{p}{1\ MPa}\right)^{c_i} \qquad [3]$$

Where:

- Z is the compressibility factor
- P is pressure
- T is temperature (in Kelvins)
- ρ is the molar gas density
- R is the ideal gas constant
- a,b,c are coefficients taken from Lemmon et al, 2008. Table 1

The molar gas density can be converted to the total mass of hydrogen in the tanks, and then changes in mass over time provide a measure of the rate of fuel consumption. Experience from working with data from vehicles that use this method suggests that data can be very noisy, so it is more useful for measuring fuel consumed over the course of a trip than for providing high frequency real time measurements.

4.3.2 Calculation of duty cycle

The relationship between a vehicle's speed and fuel consumption is well-known. Standard fuel consumption vs. speed is commonly used to predict fuel usage and emissions for various average speeds. However, these curves do not consider differences in loads, terrain, or traffic conditions, making a more sophisticated approach necessary for robust comparisons between trial and baseline vehicles.

One approach is to characterise the duty cycle using parameters like speed, load, and terrain to predict energy consumption. The energy required by a road transport vehicle is primarily used to overcome air and rolling resistance, to accelerate the vehicle, and to work against gravity. Neglecting other energy losses (energy used by refrigeration, cab heating or other ancillaries), the traction energy required in each time interval t_{j+i}-t_j can be calculated from the following equation (O'Keefe *et al.*, 2007):

$$E_{transport,j,j+1} = \frac{1}{2} \cdot \rho \cdot C_D \cdot FA \cdot \overline{v_{j,j+1}^3} \cdot \Delta t_{j,j+i}$$
$$+RRC_0 \cdot M_{veh} \cdot g \cdot \overline{v_{j,j+1}} \cdot \Delta t_{j,j+i}$$
$$+\frac{1}{2} \cdot M_{veh} \cdot \left(v_{j+1}^2 - v_j^2\right)$$
$$+M_{veh} \cdot g \cdot \left(h_{j+1} - h_j\right) \quad [4]$$

Where:

ρ is the air density

C_D the coefficient of drag

FA the vehicle's frontal area

RRC_0 the rolling resistance

g the gravity coefficient

M_{veh} the vehicle's mass

$\overline{v_{j,j+1}}$ the average speed in the time interval t_{j+i}-t_j, and

$\overline{v_{j,j+1}^3} = \frac{v_{j+1}^3 + v_{j+1}^2 \cdot v_j + v_{j+1} \cdot v_j^2 + v_j^3}{4}$.

It is assumed that each time interval t_{j+i}-t_j is small enough that the rate of change of speed (v) and rate of change of altitude (h) can be treated as constant. With a suitably high-frequency sampling rate (usually at least 1 Hz) this model can provide a good approximation of the energy required 'at the road' in each interval. Summing these over the trip enables the total energy required from the engine to be calculated.

An important aspect of this model is that it calculates the 'negative energy' required when the vehicle descends a hill or reduces its speed. The negative energy available in each time step offsets the energy required to overcome frictional losses. In a normal internal combustion vehicle, the negative energy is lost through braking. However, a vehicle with electric traction can capture and store a proportion of this energy through regenerative braking, using it to offset the positive energy required at other times in the trip. This means that the theoretical energy consumption of a vehicle with a hybrid drivetrain can be estimated for a given route, taking account of the potential for regenerative braking, if a speed and altitude trace is available for that route (O'Keefe *et al.*, 2007). Forecasting energy/fuel consumption in this way is another application of VAME.

For vehicles with significant ancillary loads, such as refrigeration, the energy calculation can be extended with additional terms for each additional load.

The energy equation shown above uses parameters specific to the individual vehicle: its loaded mass, rolling and aerodynamic drag coefficient. However, the terms in the equation can be rearranged to derive two parameters that are solely a function of the speed and terrain over a trip:

- Characteristic Acceleration (CA): a combined indicator of how much acceleration and hill climbing was undertaken during the cycle (taking account of negative energy requirement when slowing or descending): and
- Aerodynamic Speed (AS): the ratio of the cube of the speed to the average speed during the cycle, so is heavily weighted towards high speeds, reflecting the non-linear speed variance of frictional losses.

The equations for calculating these parameters using speed and altitude sampled at intervals of Δt are:

Characteristic Acceleration (*CA*):

$$\tilde{a} = \frac{\sum_{j=1}^{N-1} positive\left(\frac{1}{2}(v_{j+1}^2 - v_j^2\right) + g\,(\mathrm{h}_{j+1} - h_j))}{D}$$

[5]

Aerodynamic Speed (*AS*):

$$v_{aero}^2 = \frac{\sum_{j=1}^{N-1}(\overline{v_{j,j+1}^3} \cdot \Delta t_{j,j+1})}{D}$$

[6]

A third parameter, kinetic intensity (KI) combines the first two:

$$KI = CA/AS \qquad [7]$$

For trucks using internal combustion engine vehicles *KI* by itself can be a good predictor of fuel consumption (and hence greenhouse gas emissions) over typical drive cycles for those vehicles (Robinson and Eastlake, 2016 TBC).

When fuel consumption is measured under laboratory conditions, for example to measure the ‘official’ fuel consumption figures required for cars, they are operated on a test track or dynamometer (‘rolling-road’) over a fixed drive cycle, defined by a specified speed trace. An example of such a drive cycle is shown in Figure 7.

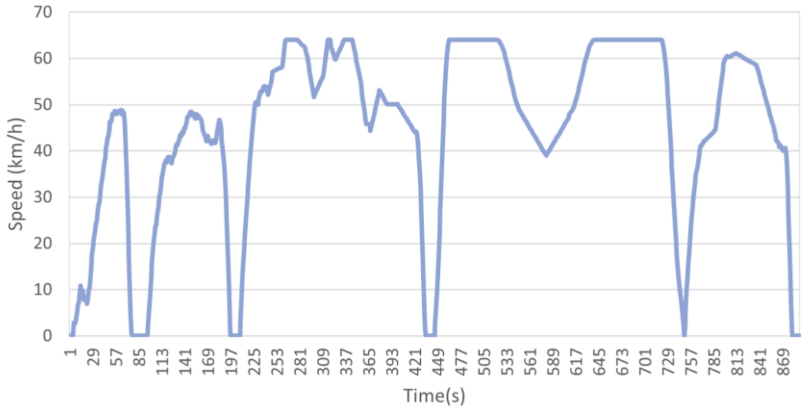

Figure 7: Speed trace for an example of a standard car drive cycle for congested traffic

A wide range of drive cycles have been developed by government and industry bodies around the world for different vehicle types (Green and Barlow, 2004), (Barlow *et al.*, 2009). These can all be characterised by the parameters discussed above, as shown in Table 1 for a selection of cycles developed by TRL and the former Warren Spring laboratory (WSL) cycles. Comparing the cycles, it is very clear that the more congested cycles, with repeated acceleration and braking, are characterised by high CA, while the motorway cycles show high AS but low CA. Through this process a trip, or part of a trip, made by a vehicle under real-world conditions can be characterised by CA and AS, and then matched with the closest standard drive cycle. If the vehicle has been tested under laboratory conditions using a standard drive cycle, then this process can be used to compare its real-world performance with the laboratory test results when driven under a comparable duty cycle. The process could also be used in reverse to forecast the fuel/energy consumption that would be expected for a proposed new vehicle, if suitable data for characterising the duty cycle can be obtained from an existing vehicle being used for the same purpose.

Table 1: Characteristics of a sample of drive cycles

Cycle Name	Distance (m)	Time (s)	Average Speed (m/s)	Characteristic Acceleration	Aero. Speed	KI
TRL WSL Motorway 113	7941	255	31.1	0.052	31.2	0.05
TRL WSL Motorway 90	7939	306	25.9	0.048	26.0	0.07
TRL WSL Rural	10949	588	18.6	0.103	21.0	0.23
TRL WSL Suburban	5513	480	11.5	0.201	13.2	1.16
TRL WSL Urban	6145	1206	5.1	0.214	8.9	2.71
WSL congested drive cycle	1915	1029	1.86	0.23	5.23	8.38

In summary, trips can be characterised using CA, AS and KI to identify duty cycles that reflect traffic conditions, speeds, and terrain. This makes it easier to ensure comparability between baseline and trial vehicles during an in-fleet trial and provides quantitative indicators that can be used in multi-factor statistical analysis to investigate the fuel/energy consumption of a new vehicle technology. Duty cycle parameters can also be used to compare real-world fuel consumption with results from laboratory tests to standardised cycles, and potentially to forecast fuel consumption for a proposed operation if suitable speed and altitude data are available. These calculations required highly granular data, collected by on-board vehicle telematics, with a minimum sampling rate of 1 Hz usually specified.

4.3.3 Calculation of heating and cooling demand

In contrast to internal combustion vehicles where waste energy can be used to heat the cabin, EVs and fuel cell vehicles face additional electrical loads for climate control, affecting their range. Air conditioning can be a significant load in summers. Heat-pumps in modern buses reduce electricity demand but still show seasonal variation. Refrigerated trucks have higher electricity requirements, making monitoring of heating and cooling loads vital for energy consumption analysis. Separate monitoring of electricity used for heating and cooling, along with traction, necessitates fitting appropriate sensors to relevant vehicle power connections and integrating them with telematics.

To optimise heating and cooling in vehicles, effective thermostatic control, and practices like keeping doors closed are crucial. Energy demand depends on the temperature difference between the inside and outside, making good temperature control important. Building energy management uses "heating degree days" (HDD): the number of degrees the external temperature is below a baseline temperature for one day (15.5°C is commonly used in the UK)[5], to analyse heating demand, and a similar approach might benefit vehicles to optimize energy use and battery range. In Motorcade, degree-day analysis was explored where possible using external temperature data from probes or third-party meteorological sources.

4.3.4 Calculation of energy consumption

As explained in Section 2.2 there are two sources of energy to consider: hydrogen, and electricity supplied through plug in charging.

The total energy supplied as hydrogen is calculated by multiplying the total hydrogen consumed in kg by the calorific value of hydrogen (33.33 kWh/kg). The total electrical energy supplied during charging is usually provided directly, in kWh, by the vehicle telematics and can also be taken from the external charging system. Depending on which sensors are fitted, energy flows to and from the battery might be directly reported in power units (kWh per sample period), or they may need to be calculated from separate voltage and current sensors (power = voltage x current).

[5] https://www.degreedays.net/

Ideally electrical power sensors would be fitted throughout the vehicle so that electrical energy flows from the fuel cell, to and from the battery, to and from the motors and to the different ancillary loads could all be quantified separately, as illustrated in Figure 8. Furthermore, if the electrical output from the fuel cell can be measured then its conversion efficiency can be calculated:

Efficiency = Electrical energy produced/ energy equivalent of hydrogen supplied [8]

However, a more limited range of sensors was provided in the trial vehicles. This meant that total energy consumption could be investigated, but it was harder to take account of the effect ancillary loads or to investigate how the use of regenerative braking is affected by duty cycle, or driver behaviour.

Battery charge is measured as State of Charge (Soc), which is the percentage ratio of remaining charge to the battery's capacity; that is

$SoC = 100 \times kWh_{remaining}/kWh_{capacity}$. [9]

SoC is an essential parameter and measured directly by the vehicle telematics. In the absence of direct measurement of power flows to/ from the battery, these can be calculated from the change in SoC with time:

Energy supplied by battery over time t1 to t2 $= (SoC_{t1} - SoC_{t2}) \times$ *Battery capacity/100* [10]

However, SoC cannot be measured to a high level of precision and is often noisy, so is not a reliable measure over short time periods.

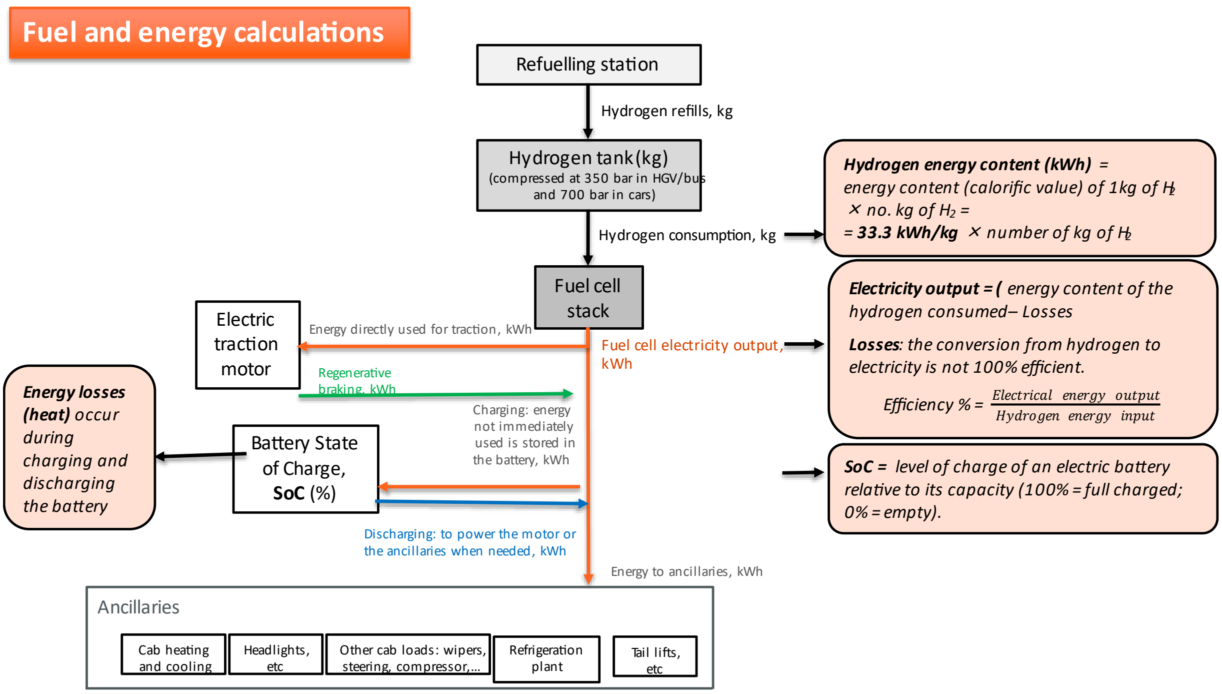

Figure 8: Summary of energy measurements and calculations, with ideal data availability

4.3.5 Calculation of environmental indicators

Environmental indicators, in particular greenhouse gas emissions (as equivalent carbon dioxide emissions, CO_2e), are calculated by multiplying the fuel (hydrogen) consumed, and electricity (kWh) supplied by an appropriate emission factor that considers all emissions arising throughout the supply chain for the energy source concerned, i.e 'well to wheel' (WTW). WTW emissions comprise 'well to tank' (WTT) emissions and 'tank to wheel' (TTW); the latter otherwise known as tailpipe emissions. For zero emission vehicles there are no tailpipe emissions to consider, so WTW emissions are the same as the WTT. For diesel, CNG, and electricity emission factors are available from the Government's guidance on environmental reporting; and also from Zemo Partnership. Because of the very wide range in WTT emissions for hydrogen, depending upon how it is produced and distributed, 'standard' WTT emission factors for hydrogen are not currently included in the government guidance. Zemo Partnership has calculated WTT emissions for a number of different hydrogen pathways (Savage and Esposito, 2021), which can be used to produce illustrative emission calculations for representative sources, for example see Table 2.

Table 2: CO_2e emission of hydrogen (Zemo Partnership)

	On-site electrolyser at bus depot, using electricity produced on site from a waste wood incinerator (gCO_2e/MJ)	Off-site electrolyser, powered by renewable electricity, road tanker delivery of compressed H2 (350kg & 340km) (gCO_2e/MJ)	On-site electrolyser at bus depot, using electricity from the UK grid (2021) (gCO_2e/MJ).
TTW	0	0	0
WTT	3.8	10.20	148.4
WTW	3.8	10.20	148.4

4.4 Implementation of the methodology

The core of the pipeline was developed using python, SQL and PowerBI. Data verification, data conditioning, data fusion and data analysis were all coded using python. Trip level summary data is stored in an SQL database and Power BI is linked to the database to generate a dashboard to present the outcomes of the analysis (Figure 9). The basic approach to implement (in the code) the analysis discussed above is described below.

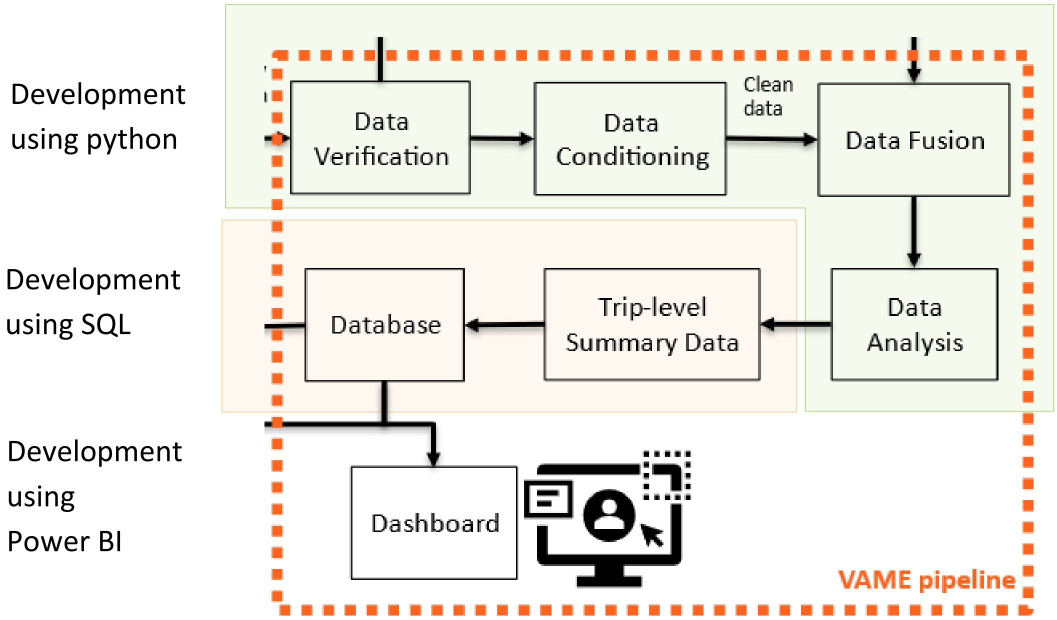

Figure 9 : Tools used for VAME tool kit development

4.4.1 Data verification fusion and analysis using python

Implementation steps:

- Constants and Variables: The constants, like the calorific value of hydrogen, emission factors, rolling resistance etc. were defined. A list of necessary variables was created, and these were used to gather the necessary parameters such as total hydrogen consumed, battery state of charge (SoC), battery capacity, vehicle ID, altitude, etc. These variables and constants are used for calculations later.
- Modularisation: The formulas/algorithms (discussed above) were broken down into separate classes and functions to promote modularity, reusability, and easier testing of the code. Each of the performance metrics (fuel, energy, duty cycle and emissions) had separate classes for their calculation. As the formulas involve simple arithmetic operations, separate functions were used to implement them.
- Comments and Documentation: Comments were added to the code to explain what each section does. This enhanced code readability and helped to understand the code's functionality.
- Data Validation: Data validation checks were included to ensure that the input data is valid and sensible. For example, to verify that SoC values are within the valid range (0-100%) and that energy values are positive.
- Error Handling: Error handling mechanisms, such as try-except blocks, we implemented to handle potential errors that might occur during calculations. This prevented the code from crashing unexpectedly.
- Testing: The code was tested with various inputs to ensure it produced accurate results.

- Version Control: Git was used to track changes and collaborate with others.

4.4.2 Storing outputs using SQL database

Dedicated tables were created to store:

- Fleet data – data listing all assets in the fleet and their corresponding properties like Vehicle ID, unloaded vehicle weight, fuel type, frontal area etc.
- Duty cycle components – pre calculated characteristic accelerations, aerodynamic speeds and kinetic intensity corresponding to speed traces for various duty cycles.
- Statistical summary – A table to store the output of the analysis. Each new statistical output is appended to the previous data.

4.4.3 Presentation of the results using PowerBI report

The outcomes of the analysis are presented in a PowerBI report (Figure 10, Figure 11):

- **Summary Cards**: High-level summary cards provide visibility of critical metrics such as fuel consumption, energy usage, emissions, and more. These cards give an overview of the fleet's environmental impact and efficiency.
- **Charts and Graphs**: Interactive line charts, bar graphs, and scatter plots are used to visualise trends over time, across different vehicles, and in relation to various parameters. These graphical representations offer insights into the variations and correlations within the dataset.
- **Maps and Geospatial Visualisation**: Geospatial maps illustrate the geographical distribution of the fleet's operations.
- **Filters and Slicers**: The dashboard incorporates filters and slicers that allow users to customise their view by selecting specific time periods, vehicle IDs, fuel types, and other relevant parameters.
- **User-Friendly Navigation**: The Power BI dashboard employs a user-friendly navigation structure that guides users through different sections and components. Interactive elements, such as clickable buttons, and tabs, facilitate seamless movement between various parts of the dashboard, ensuring that users can quickly access the information they seek.
- **Set up data export and sharing**: These reports can be easily shared either by giving access to the PowerBI workspace (a Power BI licence is required) or sharing PDFs.

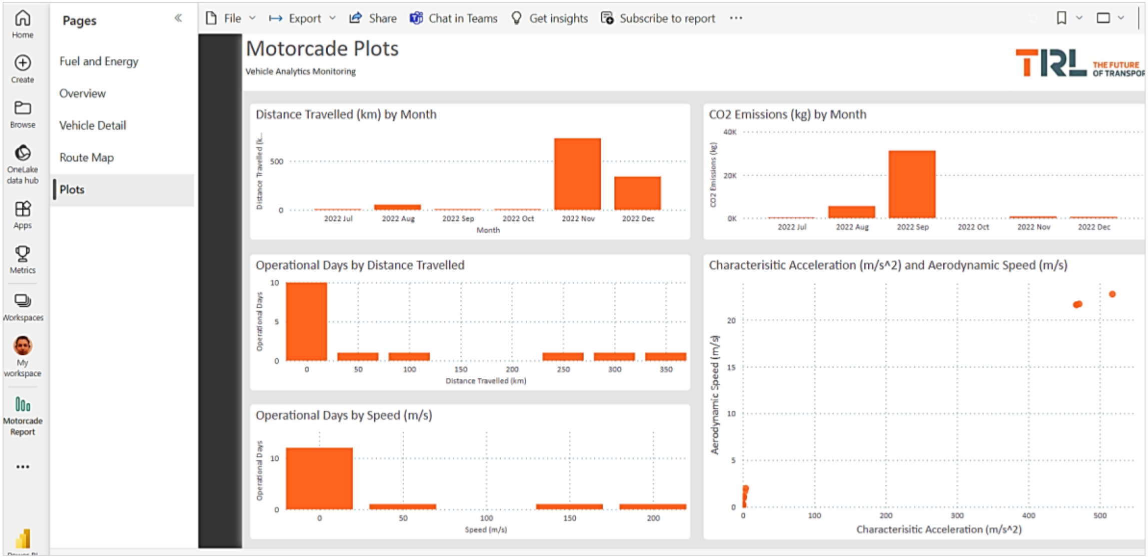

Figure 10: Example of VAME output – performance metrics

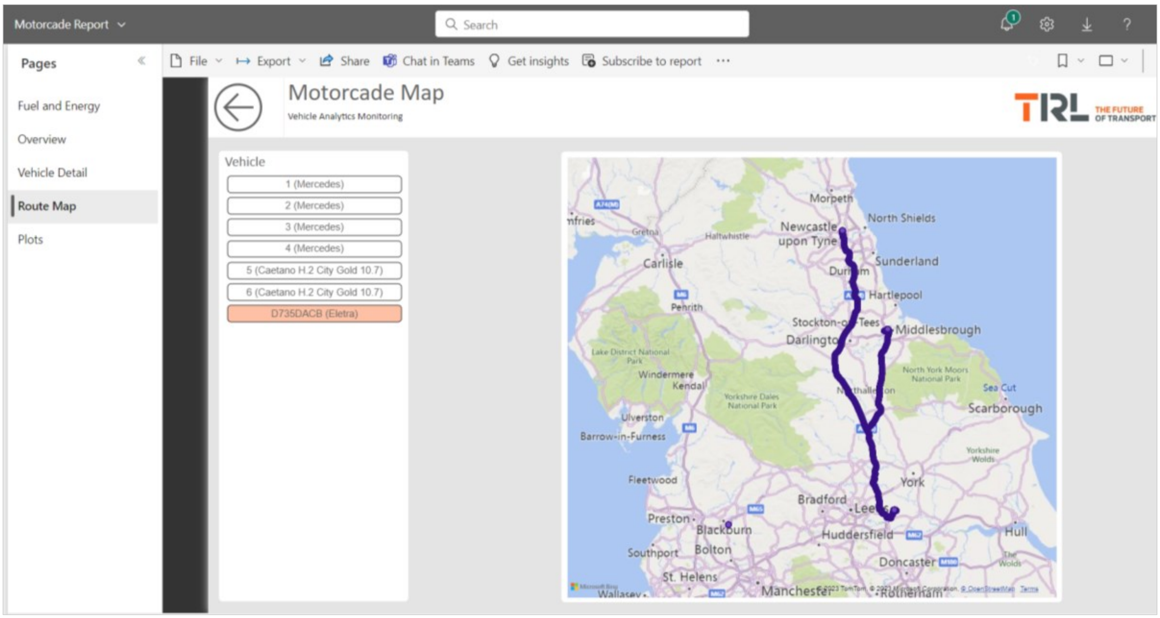

Figure 11: Example of VAME output – route maps

5 Review of toolkit analysis

This section presents the outputs from testing the VAME toolkit with samples of data from the demonstration projects. The purpose of this section is to assess and discuss the ability of the toolkit to undertake the required analysis with the available data, identifying how well the outputs compare with what would be expected for those vehicles under the circumstances in which they were being operated.

5.1 Operational statistics

The first level of reporting in the VAME toolkit summarises the type of operation that the vehicle has undertaken. Key indicators are distance driven and operating hours and average speed. Figure 12 shows the daily distance and hours of operation for the hydrogen bus throughout the demonstration period. This highlights the large variation in daily operation, reflecting the unusual nature of the trips made during the demonstration (compared with the much more consistent daily duties that would be expected of a vehicle operating in normal passenger service). On some days the vehicle was just being moved from site to site, or on stationary display. This chart demonstrates the value of this VAME output in providing a quick visual overview of how a vehicle has been operated over the time period of interest. This helps to provide context when interpreting performance data and to enable a check to made of consistency of duties and comparability with those of other vehicles.

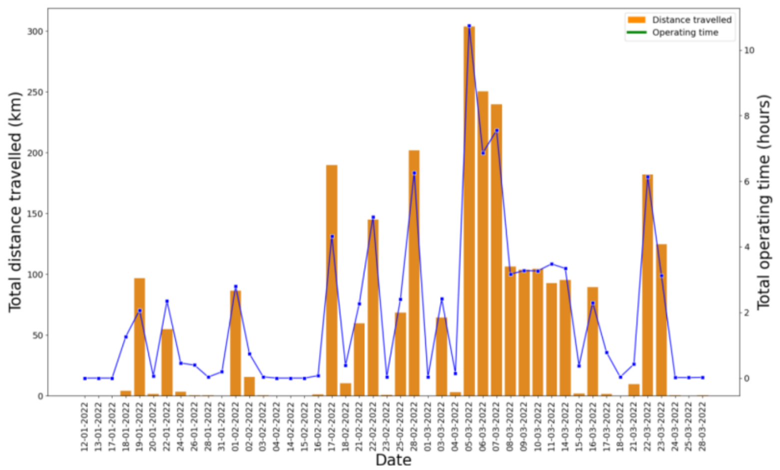

Figure 12: Total daily distance and operating hours (bus)

5.2 Speed and drive cycle analysis

5.2.1 Duty cycle analysis with bus data

As discussed previously, speed, and the distribution of speeds throughout the trip, have a significant impact on overall energy consumption. Figure 13 shows an example of a speed trace for the hydrogen bus, taken on 6 March 2022; one of the days with highest total mileage driven. A very clear stop-start pattern is seen, reflecting a more usual bus duty cycle. Figure 14 shows daily average speeds, showing that on 6 March the average speed was just over 35 km/h.

Figure 13: Speed trace for an example day (bus)

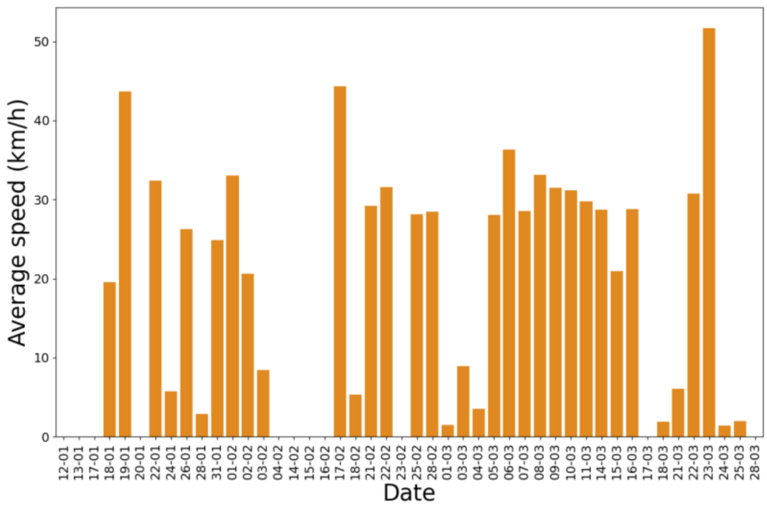

Figure 14: Daily average speed (bus)

These sample outputs also provide quick visual overviews of how the vehicle has been operated, the wide range of reported average speeds being consistent with the wide range of routes and locations over which the bus was driven. Any days where there was unusual operation can be quickly identified in the daily average speed chart, and the corresponding speed trace then examined in greater detail.

Data on the speed, route length and ascent/descent were used to characterise the bus's drive cycle by Characteristic Acceleration (CA), Aerodynamic Speed (AS) and Kinetic Intensity (KI) (as defined in Section 4.3.2), on days where sufficient quality GPS data was available. The calculated drive cycle parameters are shown in Figure 15, along with curves of constant KI, for a range of bus drive cycles.

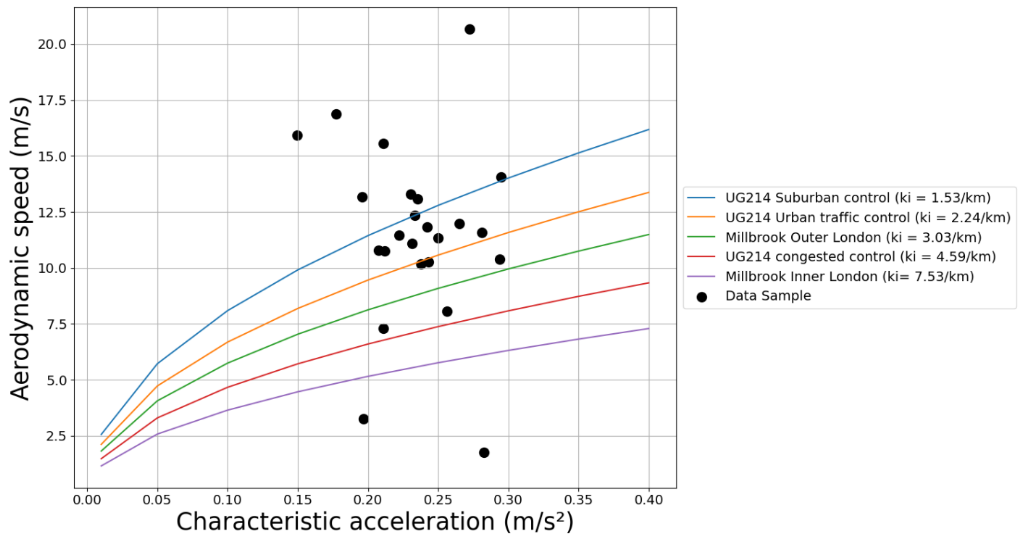

Figure 15: Aerodynamic speed and characteristic acceleration of the bus analysed by trip

A wide range can be observed, consistent with what would be expected for the variety of trips undertaken. Overall, most trips during the demonstration projects were found to match outer urban and suburban drive cycles, rather than the most congested urban cycles. This is consistent with the demonstration routes on which the vehicle was used, which were distributed around the region, with significant distance driven between different towns, rather than being focused on urban areas. Note that the highest sampling interval used in the bus trial was 10 seconds rather than the 1 second preferred for drive cycle analysis. This limits the accuracy of the analysis. Nonetheless, the results are still consistent with what would be expected for the types of trip undertaken in the demonstration projects, and show that VAME can be used to match real-world driving conditions to standard drive cycles. This has benefits for the future use of VAME, because drive cycle analysis can be used in in-fleet trials to ensure that when different vehicles are compared with each other the reported fuel/energy consumption data is for comparable driving conditions.

Drive cycle characterisation also enables data from in-fleet trials to be compared with data from research literature, or with results from standardised tests, such as those carried out by Zemo Partnership to demonstrate that a vehicle qualifies as Low Emission, Ultra Low Emission or Zero Emission[6].

5.3 Fuel/ energy consumption and use

5.3.1 Bus fuel and electricity consumption

The demonstration project bus was powered by a fuel cell but could also be plugged-in to the grid so that the battery could be recharged using mains electricity. This means that, in principle, there are two sources of energy to consider; however plug-in charging was not used during the demonstration projects.

[6] https://www.zemo.org.uk/work-with-us/buses-coaches/low-emission-buses/low-emission-bus-testing.htm

The hydrogen bus telematics reported hydrogen consumption directly, in mass units. The total hydrogen consumed from January 2022 to March 2022 was 176 kg. Figure 16 shows the total monthly hydrogen consumption during the trial, as calculated by VAME from the telematics data. The increasing consumption by month is consistent with what would be expected for the observed increase in distance driven in the later months of the demonstration project period, and with the refuelling records of the operator.

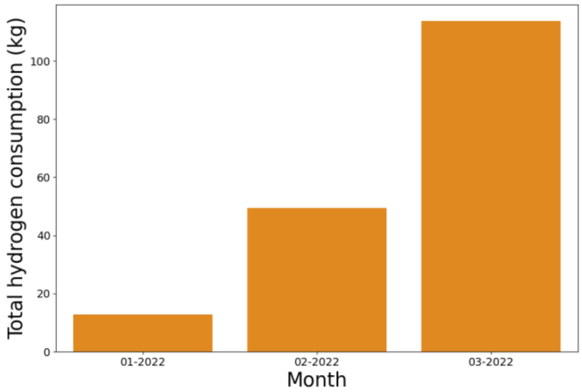

Figure 16: Hydrogen consumption by month (bus)

Taking account of the distance driven over the whole monitoring period, the bus consumed on average 5.9 kgH_2/100 km, very close to the average of 6 kgH_2/100 km reported by Caetano for normal service conditions. This is despite the high proportion of very short trips undertaken during the demonstration project, which would be expected to result in greater overall energy consumption because, amongst other things, energy is used when the fuel cell is initially brought up to operating temperature at the start of the working day. This loss would be more significant on days with overall low mileage driven.

The energy content of the hydrogen is obtained by multiplying the hydrogen's calorific value of 33.3 kWh/kgH_2 (that is the content energy of one kilogram of hydrogen, lower heating value) by the quantity of hydrogen consumed. Figure 17 shows the monthly energy supplied as hydrogen consumed in the fuel cell (in kWh). Table 3 summarises the monthly hydrogen consumption per 100 km and the corresponding energy consumption per kilometre.

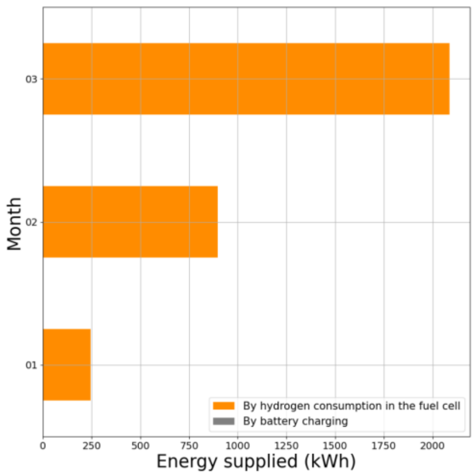

Figure 17: Total energy supplied by month (bus)

Table 3: Hydrogen and electricity supplied summary (bus)

Month	Average hydrogen consumption (kg/100km)	Corresponding hydrogen energy consumption (kWh/km)	Electricity provided by battery charging (kWh/km)	Total energy consumption (kWh/km)
01-2022	5.54	1.85	0	1.85
02-2022	5.94	1.98	0	1.98
03-2022	5.99	2.00	0	2.00
	5.94	**1.98**	**0**	**1.98**

The average (chemical) energy consumption per km (hydrogen) was 1.98 kWh/km. The electricity produced by the fuel was reported by the telematics and used to calculate the fuel cell's conversion efficiency. The efficiency of the fuel cell was estimated by dividing the measured energy generated by the FC by the hydrogen energy supplied:

FC efficiency = Electrical energy generated by the FC in kWh / energy content of the hydrogen consumed in kWh [11]

Table 4 reports monthly hydrogen consumption, the electrical energy produced by the fuel cell and the calculated conversion efficiency. The overall average efficiency during the bus trial was 55%, which is towards the higher end of the values expected for a PEM FC in a mobile application. This VAME output shows how efficiency calculations can be used to provide a quick overview of the fuel cell system's performance, enabling any unusual behaviour to be identified for more detailed investigation.

Table 4: Hydrogen supplied, electricity generated and energy efficiency (bus)

Month	Total hydrogen consumed (kg)	Equivalent energy (kWh)	Total electricity generated by fuel cell (kWh)	Fuel cell efficiency (%)
01-2022	12.7	423	246	58%
02-2022	49.5	1,649	897	54%
03-2022	113.7	3,787	2087	55%
Total	**175.9**	**5,858**	**3229**	**55%**

5.3.2 Truck fuel and electricity consumption

As explained in Section 4.3.1, unlike the bus, for which the telematics reported cumulative hydrogen consumption in mass units, hydrogen consumption for the truck had to be calculated using data from temperature and pressure sensors fitted to each of the four storage tanks. Furthermore, the temperature sensor output was the voltage measured across a thermistor, so had to be converted to temperature by means of a thermistor calibration curve. Figure 18 shows an example of the calculated total mass of hydrogen remaining in the tanks during a sample trip, following refuelling.

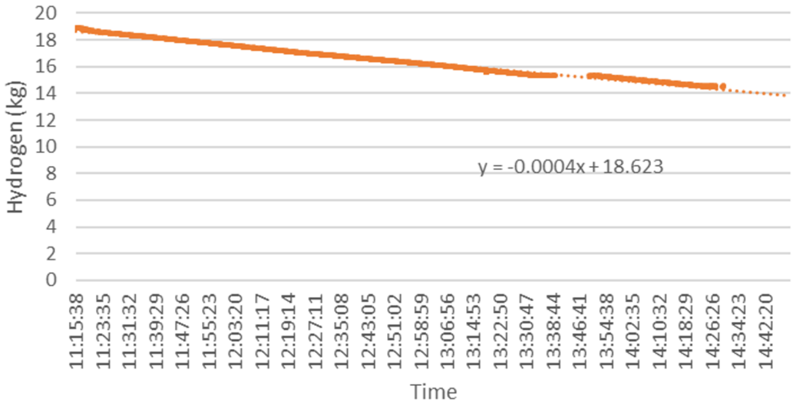

Figure 18: Calculated hydrogen remaining in tanks during a sample trip

The starting mass is consistent with the maximum capacity of the tanks (~19.5 kg) and shows a fairly constant rate of consumption, as would be expected for a fuel cell being operated at a steady output power. Fitting a best fit line to the mass gives a slope of 0.37 g/s, or 1.34 kg/hr. As hydrogen has a calorific value of 33.3 kWh/kg, this corresponds to a power consumption of 44.7 kW; slightly higher than the maximum of 43 kW expected from the vehicle specification. Nonetheless, given that no separate calibration was undertaken, this result is within expectations and demonstrates that hydrogen consumption can be calculated from the raw sensor data if required.

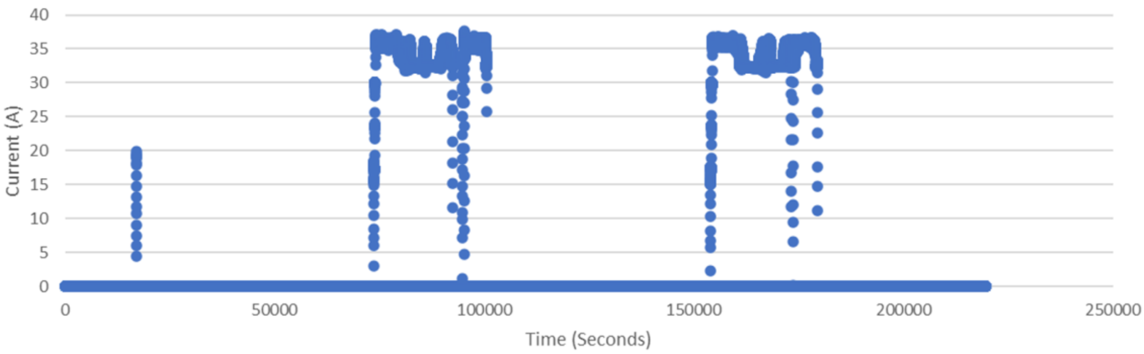

Figure 19: Example of fuel cell output current

In the data available for the trial the truck's fuel cell management system reported the output current rather than power, as this was needed for diagnostic purposes (Figure 19). Current can be converted to a power measurement by multiplying by the voltage across the fuel cell. While a voltage reading taken at the fuel cell would have been preferred, a voltage measurement was provided from the input to the DC:DC converter used to provide the low voltage power supply. This was approximately 715 V, varying from about 690 V to 720 V. There was considerable noise in the data at 1 Hz, reflecting the transients and electrical noise that would be expected in a vehicle. Figure 20 shows the power output calculated at 1 Hz using those voltage and current readings.

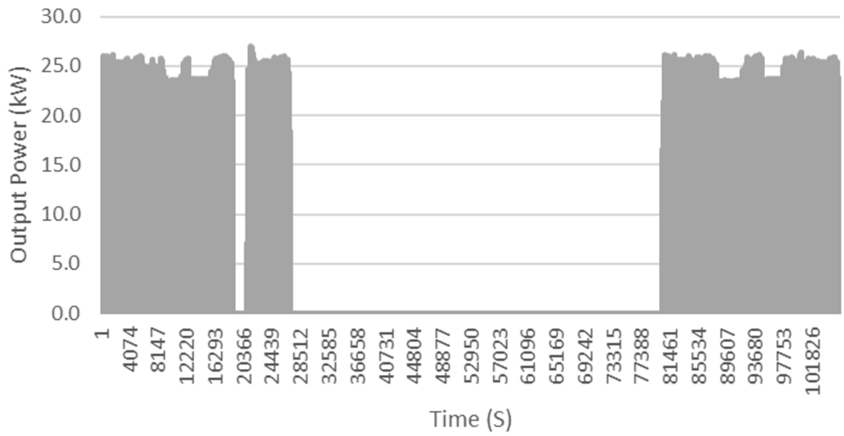

Figure 20: Calculated output power (fuel cell current x DC voltage)

The calculated output power is 23 to 25 kW, compared with the nominal 21 kW that would be expected from the vehicle specification. For the nominal 43 kW power consumption stated in the specification, an output of 21 kW implies that the conversion efficiency of the fuel cell is around 50%, which is consistent with the calculated values for hydrogen consumption and electrical power production.

5.4 Energy consumption by end use

As well as powering the traction motors, the fuel cell must also supply energy that is used to heat or cool the bus interior (by means of a heat pump) and for other ancillary purposes such as lighting, air compressor, power steering, boarding ramp. Some of these demands, in particular heating and cooling, can represent a significant part of the vehicle's overall energy consumption, affecting range and energy costs. It is therefore necessary to be able to analyse traction energy separately from other loads in order to understand and optimise their use, and to control for their effects on fuel consumption when undertaking trials. The telematics data reported energy consumption by various loads, which are reported below.

Figure 21 shows the total energy consumed in the 20 operational days of the bus trial period, broken down by net traction energy, heating and cooling, and other ancillary loads. Two-thirds of the energy went for traction, while the remaining third was used by heating/cooling and other ancillaries. NB: this excludes any net changes in the battery SoC over the period and battery losses. Please note that Caetano advised that the other ancillary energy measurements may be unreliable, so the figures shown below should be regarded as illustrative and used only for the purposes of demonstrating the methodology. This demonstrates the value of being able to provide a breakdown of energy uses in VAME, because heating and cooling can have a significant impact on range so having summary reports makes it easier to ensure that these loads are managed optimally.

In addition, as the bus is equipped with regenerative braking, which returns a proportion of the energy supplied to the traction motors, it is necessary to take account of the energy regenerated when calculating the overall energy required to operate the vehicle. The analysis therefore focuses on "net traction energy", being the energy supplied to the traction motors minus the energy regenerated. Energy also flows to and from the battery, resulting in changes in its State of Charge (SoC), and losses will occur within the battery.

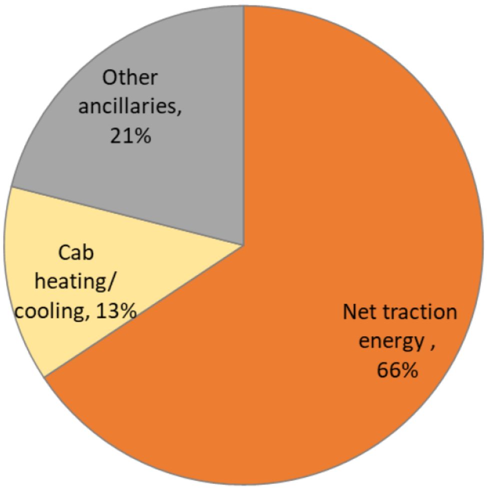

Figure 21: Energy used by purpose (bus)

5.5 Use of regenerative braking

The regenerative braking efficiency is defined as:

Regeneration efficiency = Energy regenerated by the motor / Energy consumed for traction *[12]*

The average regeneration efficiency over the trial period was 38%. However, this varied significantly between individual trips, reflecting their diversity in terrain, traffic conditions and nature of trip, all of which affect the drive cycle.

Traction energy is highly dependent upon the drive cycle. Figure 22 plots the daily regenerative braking energy per km against the kinetic intensity. Although there is a degree of scatter, and some outliers, there is a clear relationship between increased KI and increased regenerated energy. As more regenerative braking would be expected for drive cycles involving repeated acceleration and braking at higher road speeds, or on hilly terrain, the regenerated energy would therefore be expected to be higher for drive cycles with high KI.

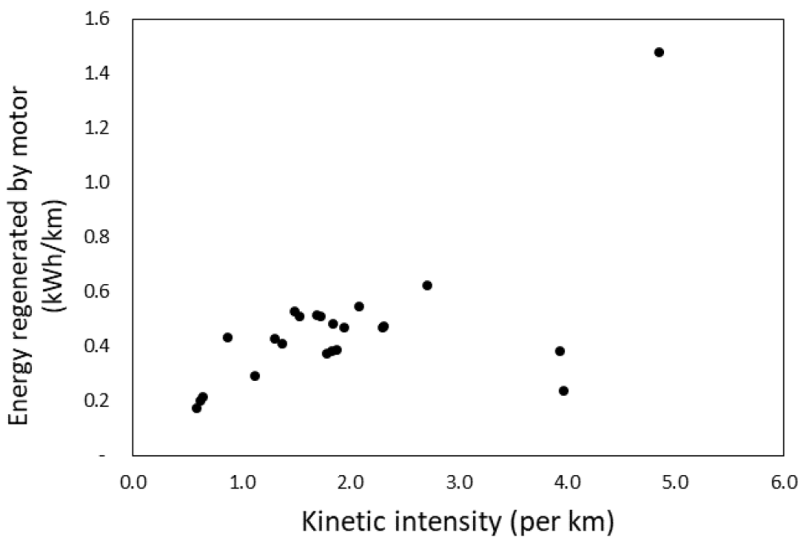

Figure 22: Energy regenerated vs Kinetic Intensity (bus)

As explained previously, the accuracy of drive cycle calculations for the bus was limited using data at a sampling interval of 10 seconds rather than the 1 second preferred for such analysis. The observed results should therefore be illustrative of the method used. nonetheless, the benefits of regeneration in high KI drive cycles can be observed. Analysis of regenerative braking and drive cycles can be used to optimise energy efficiency of the vehicle in service, for example by identifying where driver training could be beneficial.

5.6 Analysis of heating and cooling demand

To investigate the relationship between external temperature and heating demand, the vehicle telematics were used to provide an external temperature reading as well as energy consumed by the heat pump. It is important to bear in mind that the data had not originally been collected for this purpose and errors and missing data were found. Furthermore, there were widely varying daily operating hours and journey lengths, with many very short operating days that wouldn't provide time for internal temperature to stabilise. A strong relationship between external temperature and heating energy would not therefore be expected with this sample. Nonetheless, the opportunity was taken to use the data for illustrative purposes only, to demonstrate the methodology.

Because of the wide range in operating hours the heating energy was normalised by the hours that the vehicle was drawing power, using the 'engine on' field. Days when the bus was driven for less than 1 hour were not included to ensure there was more time for the internal temperature to stabilise. A scatter plot of the daily heating energy per hour vs daily average external temperature is shown in Figure 23. While significant scatter can be observed, as would be expected for this sample, there is a group of daily trips that show an overall trend where heating energy was lower on days with a higher average external temperature. However, linear regression was not undertaken with the available data, giving its known limitations.

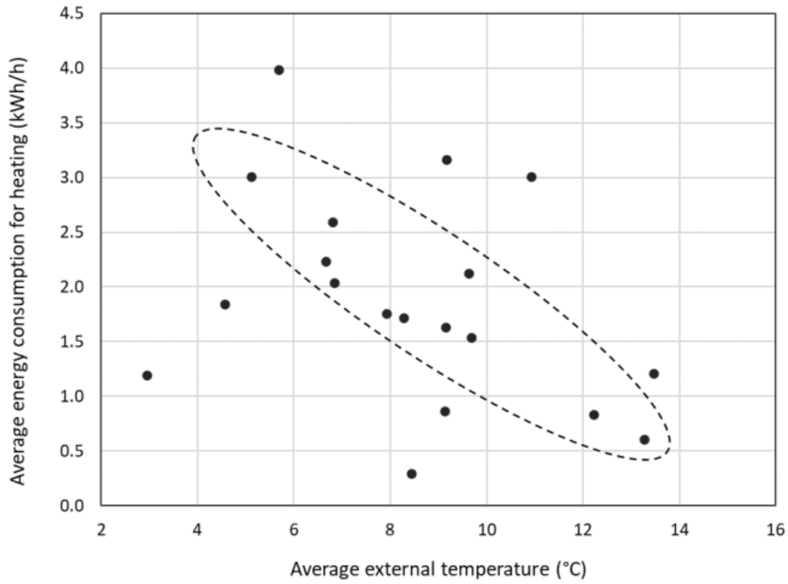

Figure 23: Illustrative plot of heating consumption vs average external temperature

6 Discussion

6.1 Application of the VAME toolkit for vehicle analytics

The toolkit was tested with samples of data from two vehicles while in operation. However, the two vehicles differed substantially in the sensors fitted and data available. The truck was a prototype while the bus was a production vehicle. This was helpful to provide experience on the effects of data sources, ensuring that the toolkit was not limited/biased to one particular vehicle type. The data samples assisted in the development of the toolkit through an iterative process – with an initial review of the data used to inform code development, followed by testing and further review of the modules.

The toolkit was able to generate summary outputs and indicators for both vehicles, including a ‘dashboard’ to simplify performance reporting. The toolkit also generates operational indicators, such as daily distance, time, average speeds from the raw data that were consistent with the known operations that the vehicle had undertaken during the demonstration period. The following paragraphs consider the lessons learnt with regard to the ability of the toolkit to report performance. We discuss the lessons learnt regarding the software component of the toolkit itself in Section 6.2.

By using the hydrogen consumption data provided by the telematics, the toolkit was able to calculate the energy and emissions indicators for the bus, including overall average hydrogen consumption per 100 km. The figures were consistent with the manufacturer’s expectations for normal bus operations. As the truck telematics did not report hydrogen consumption directly this had to be calculated from temperature and pressure measurements from each of the four tanks. The temperature in turn had to be calculated from the recorded voltage across a thermistor using a function implanted in the toolkit. The calculated hydrogen consumption rate was about 10% greater than might be expected for the specified fuel cell, but followed the expected usage pattern where the fuel cell is operated at a steady power level and the batteries provide peak power demand. It was not practicable to undertake any calibration checks of the sensors. The accuracy of the measurement should be improved with calibration.

When monitoring vehicles with electric traction it is desirable to monitor ancillary loads (such as heating) separately from traction energy, so that measured performance is not affected by external factors such as weather conditions. This also enables analysis of how vehicle range is affected by heating and cooling loads, which would help operators to optimise performance by taking these loads into account. The bus telematics system did report the energy supplied to the heat pump (used for saloon heating and cooling), although there were some problems with the accuracy of these sensors. The toolkit successfully undertook the required analysis, to produce a summary of energy consumption by end use. As this has a significant effect on energy use, we would recommend that the required power sensors are included when considering the application of the VAME toolkit to other vehicles.

One of the objectives of the toolkit was to facilitate detailed analyses of drive cycles, using indicators such as kinetic intensity. A wide range of kinetic intensity was calculated for the trips undertaken in the demonstration projects, corresponding to a number of different theoretical drive cycles. This is consistent with the range of routes on which the bus was driven during the demonstration, in urban areas as well as on rural routes between towns. The overall results were, at least qualitatively, consistent with what would be expected for the types of trips undertaken. This suggests that the toolkit could be used to match real-world driving conditions to standard drive cycles. This has benefits for the future use of the toolkit, because drive cycle analysis can be used in in-fleet trials to facilitate the comparison of vehicles in comparable driving conditions (a like-for-like basis). Drive cycle characterisation also enables data from in-fleet trials to be compared with data from the research literature, or with results from standardised tests undertaken by manufacturers or government bodies. Finally, drive cycles could also be used to predict the theoretical fuel consumption of a hydrogen bus on a proposed route (using GPS drive cycle data collected by a suitably equipped existing diesel vehicle) and, for example, used to specify the size of the hydrogen tanks.

The opportunity was taken to investigate the relationship between average hourly heating energy demand and the external temperature measurement. As the bus was not used for comparable duties each day, very little correlation could be seen, as would be expected. However, the analysis provides evidence that this data could be used to monitor and optimise heating control and its impact on range for buses in operation in regular and consistent services. A larger sample of data from a bus used in a normal service would enable more sophisticated analyses to be undertaken. These could build on established techniques used to manage energy consumption in buildings, such as the use of Degree Days, as described in Section 4.3.3. This could be used to predict energy demand from local climate data.

6.2 Lessons learnt / performance and potential improvements to the toolkit (software)

The availability of two different sources of telematics data from the demonstration also supported the development of more robust and better understood processes within the toolkit software. The wide range of data provided the opportunity to better understand the characteristics of the raw data, observe data bottlenecks, validate the repeatability, and iteratively refine the toolkit.

For example, the data gathered through the API was inherently noisy, with missing values, data captured at different frequencies that required collation, and many parameters to be handled (making it difficult to separate high frequency signals from low frequency signals). This is challenging to achieve even when data delivery is consistent - which was not the case during the demonstration trials. Therefore, rigorous validation and correction processes were implemented. These processes are costly in terms of development time and computation time. It was found that the noise, missing values and data inconsistency were different for data from different telematics systems. Therefore, specific approaches to data conditioning had to be developed and applied for each data type. This was achieved by interrogating the data and observing trends and outliers. The efficiency of this development phase was improved by developing and maintaining a ‘data template’ to define the parameters, their units, and value thresholds corresponding to those units. As each new data type was addressed this interrogation exercise was carried out to populate the template. There is a likelihood that these data conditioning requirements will need to be manually developed during the development stage of any VAME toolkit that accommodates future (new) data sources. However, after development the processes can be applied for automated conditioning and processing with the results stored in the SQL database, linked to the Power BI report.

The toolkit was initially developed using on-premises IT infrastructure, using the bus demonstration data, which gave a good head start whilst considering the development requirements for implementation using Azure services. The transition to the cloud solution opened avenues to scale the toolkit to meet the increasing data needs and provide easier access to the data. It is noted that there is a need to consider the costs associated with the use of Virtual Machines on the cloud. During this project the team took an approach in which Virtual Machines were released when testing was not being carried out, deploying them again when the code pipeline was being tested. This reduced the overall costs, but the approach was not automated in the toolkit development. This may need to be considered for longer term development/implementation.

7 Conclusions and Recommendations

Motorcade aimed to develop and test a new VAME toolkit that could provide standardised methods to compare the performance of vehicles deploying different fuel technologies. To develop the toolkit, the project has obtained a deeper understanding of how to handle telematics data, including granular data errors, inconsistencies, spikes, missing data, uneven granularity, sparsity, ambiguity in units of measurement, unrealistic data values, and disparate methods of capturing fuel utilisation. This understanding has been applied in the development of conditioning, processing and analysis tools that have been implemented within an Azure-based VAME toolkit.

The project has developed standardised metrics for reporting performance in the toolkit, enabling comparison of performance across a range fuel technologies and vehicle types on a common baseline. By applying data from both bus and truck demonstration trials Motorcade has shown how a VAME toolkit can be applied to compare fuel, energy (excluding energy demand due to weather), duty cycle, emissions and cost across vehicles using electric and hydrogen technologies (and diesel and petrol using the outcomes of our previous work on VAME). However, we can recommend further refinements that would improve the capability of the toolkit, which would include:

Range of data: Although work has been undertaken with a range of data types, according to the telemetry installed on the demonstration vehicles, to achieve the benefits of monitoring using a fully functional VAME toolkit we recommend that the test vehicles would be equipped with a full range of sensors, as discussed in this report, to provide data at the required sampling rate (at least 1 Hz). A data specification has been prepared based on the experience gained from Motorcade and it is strongly recommended that this is followed when specifying vehicles for future trials (Appendix A).

Calibration: It was not practicable to undertake calibration of the sensors deployed on the demonstration vehicles. It would be expected that the accuracy of the performance measurement could be improved with calibration.

Data Conditioning: Incorporating more advanced statistical and machine learning techniques for pattern recognition and anomaly detection may improve the robustness of the data conditioning.

Optimisation: The toolkit is currently implemented as one item of code. This could be broken into smaller modules to focus on each metric to improve efficiency and upgradeability. This could be easily achieved using cloud services.

Visualisation: Ensuring that the generated reports are user-friendly and easily understandable by non-technical users will be important. The reporting tool requires refinement – e.g. clear labels, tooltips, and intuitive interactions could enhance the user experience, and the Power BI report could include a landing page which explains the tool capabilities. **Documentation and user guides** could also help users understand how to use the toolkit effectively and facilitate adoption of the toolkit.

GDPR: to incorporate driver and behaviour data, there may be a need to consider data privacy and security regulations.

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Appendix A Detailed data specification for monitoring a trial

This specification sets out the data that would be requested from a vehicle operator when undertaking a trial.

Information about the vehicle specification, requested at start of trial				
	Parameter	**Description**		**unit**
Fuel Cell (FC)	**Brand and model**			Text
	PEM	*Type*		Text
	Rated maximum output			kW
	Rated maximum voltage			V
	Power generation efficiency			%
	Hydrogen flow to FC - method of measurement	*E.g. flow meter, calculation from temperature and pressure,…*		Text
	Additional details	*Additional available information such as, air cooled, max power, thermal cycle capability, mass, volume power density kW/L or mass power density kW/kg, etc.*		
Tank	**Mass**			kg
	Storage density	*Hydrogen storage mass per tank weight*		wt%
	Volume	*Internal volume*		L
Battery	**Battery type**	*Battery chemistry*		Text
	Battery capacity			kWh
	Depot charging?	*Please confirm whether other separate charging will be undertaken*		Yes/No
	Additional details	*Other available information such as*		

		age, V, Ah, active cooling/heating, etc.		
Vehicle	**Mass**			kg
	Length			m
	Rolling resistance coefficient			number
	Frontal area			m^2
	Aerodynamic coefficient			number
	Motor type	*Description of the motor*		text
	Power motor			kW
	Final drive ratio			number
	Wheel base			m
HRS	**Method of refuelling**	*Pressure, communication between vehicle and station (handshake)*		
Data to be provided by vehicle telematics				
	Parameter	**Description**	**Frequency**	**unit**
Hydrogen tank and FC	**Time stamp**	*Date and time*	1Hz	dd/mm/yyyy hh:mm
	Quantity of hydrogen in fuel tank (kg) or hydrogen 'state of charge' SoC (%) [depending on the method available]	*SoC = ratio of hydrogen density to the full-fill density.*	1Hz	kg or %
	Hydrogen consumption by fuel cell [depending on the method available]	*Flow rate (g/s) or mass consumed during sampling period (g).*	1Hz	g/s or g
	Electrical energy generated		1Hz	kWh

	Fuel cell temperature		1Hz	°C
	Power		1Hz	kW
	Stack voltage		1Hz	V
Battery	**State of Charge (SoC)**		1Hz	%
	Energy charged to battery by FC		1Hz	kWh
	Energy charged to battery by regenerative braking		1Hz	kWh
	Energy for traction		1Hz	kWh
	Energy for heating/airconditioning	*Energy used for heating and cooling the cab*	1Hz	kWh
	Energy for other ancillaries	*Energy used for lights, …*	1Hz	kWh
	Energy charged to battery by plug-in	*If applicable, otherwise omit*	Per event	kWh
Trips	**Trip ID**		Per trip	Number
	Anonymised driver IDs		Per trip	Number/Text
	Load (or Transport work)	*Calculated by telematics or measurement from suspension pressure.*	Per trip	t (or tonne-km)
	Timestamp	*GPS time*	1Hz	dd/mm/yyyy hh:mm
	Odometer reading		1Hz	km
	Coordinates	*GPS longitude and latitude*	1Hz	Decimal degrees or Degrees, minutes, seconds
	Altitude	*GPS altitude/elevation*	1Hz	metres
	External temperature		1Hz	°C
	Position of vehicle's brake pedal	*Ratio of current position to max. position*	1Hz	%

	Position of vehicle's accelerator pedal	*Ratio of current position to max. position*	1Hz	%
	Speed		1Hz	km/s
Refuelling events	**Start timestamp**		Per event	dd/mm/yyyy hh:mm
	Duration (or end timestamp)		Per event	hours (or dd/mm/yyyy hh:mm)

Motorcade

Analysis toolkit for monitoring trials of zero emission vehicles

The UK Government's climate change strategy has set ambitious targets to decarbonise transport. To support this the government has funded several programmes to develop new vehicle technologies and fuel/energy supply chains. To understand the performance of these new technologies there is a need for standardised tools that capture vehicle data and provide assessments of energy use that can be applied to compare energy consumption objectively. Such tools should also be capable of monitoring fleets of vehicles, to support evidence-based decision-making and strategic planning regarding the deployment of fleets employing new fuel types.

This fleet performance monitoring tool has been the focus of the Motorcade project. Motorcade has drawn on data from two hydrogen vehicle demonstration projects providing telematics data on energy consumption to develop an Azure-based VAME (Vehicle Analytics for Monitoring and Evaluation) toolkit which collates, cleans, processes and interrogates telemetry data to obtain standardised metrics for reporting performance, reported in a Power BI dashboard. The toolkit is able to compare fuel, energy (excluding energy demand due to weather), duty cycle, emissions and cost for vehicles that deploy using electric and hydrogen technologies.

Other titles from this subject area

MIS072	Low Emission Bus Scheme monitoring, Final Report. F Ognissanto & M Jones, 2022
PPR967	Driving and accelerating the adoption of electric vehicles in the UK, C Reiner, G Beard, T Park & N Kinnear, 2020
PPR978	Low Emission Freight & Logistics Trial (LEFT) Dissemination Report. Brian Robinson, LowCVP Partnership, 2020
XPR110	Use of in-vehicle technologies to assist with and encourage safe and efficient driving, V Pyta, L Verwey, S Chowdhury, J Hitchings, N Harpham, S Helman, M Edwards & Waka Kotahi, NZ Transport Agency research report 691 2022

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