Design and Modeling for Hydrogen Fuel Cell Conversion of Parcel Delivery Trucks

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***Abstract*—With an emphasis on reducing fossil fuel consumption and emissions, major delivery service corporations have begun deploying and operating Class 6 zero emissions delivery vans. Battery electric delivery vans are currently available, but their range is a limitation and doesn't offer flexibility in assigning vehicles to delivery routes. Fuel cell hybrid delivery vans offer a zero emissions solution with extended range and route planning flexibility. In a competitive market, a delivery van design that trades the fuel cell and battery size, performance, and cost is critical to the success and adoption of these zero emissions trucks. This paper outlines a systematic approach using real world operational data and duty cycles to properly size the fuel cell and battery for a zero emissions hybrid delivery van. The approach uses real world GPS data to define routes and duty cycles, along with vehicle powertrain models to assess performance capabilities. The study suggests that a 32 kW fuel cell power system paired with a 49 kWh battery energy storage system and 15 kg of hydrogen storage is a desired option to complete the most demanding parcel and delivery duty cycles.**

Keywords—fuel cell; hydrogen; hybrid electric vehicle; medium-duty truck; vehicle modeling; zero emissions

I. INTRODUCTION

Major delivery service corporations operate over 250,000 vehicles globally for parcel delivery services. The majority of these vehicles are diesel powered, and there is a strong interest in deploying technologies in commercial fleet applications that reduce dependency on fossil fuels and operate with zero emissions. For example, UPS currently operates 3,000 alternative fuel vehicles, while FedEx has already reached a 2020 target for a 30% increase in vehicle fuel efficiency [1, 2]. For the traditional Class 6 walk-in delivery vans that are commonly seen on delivery routes in North America, manufacturers offer zero emission battery powered versions that operate with approximately 100 kWh lithium-ion battery packs and have an advertised range of 55 – 100 miles, depending on route conditions and payload. A study by Argonne National Laboratories suggests that a more cost effective method to extend range is to utilize hydrogen storage and PEM fuel cells while downsizing the lithium ion battery to handle high powered transients [3].

In order to demonstrate hydrogen fuel cells for range extension of Class 6 walk-in delivery vans, and increase market penetration of the technology, The University of Texas at Austin Center for Electromechanics (UT-CEM) is partnered with the Center for Transportation and the Environment (CTE) and Unique Electric Solutions (UES) to convert up to 16 diesel powered vans to fuel cell hybrid configurations. (This work is sponsored by the US Department of Energy, California Energy Commission, and South Coast Air Quality Management District.) UT-CEM and CTE have led conversions of electric utility vehicles with hydrogen fuel cells to increase operational range from 35 miles to over 300 miles [4].

This paper presents the methodology UT-CEM and CTE employ to define route profiles for vehicle modeling through acquisition and post-processing of real world GPS data. Route data collection and vehicle modeling are required to understand operational vehicle loads to properly size the fuel cell module and battery for transient storage. Section II of this paper outlines the methodology for data collection and data post-processing. Section III discusses methodologies for performing the sizing trade study on two selected routes from the collected data set. The final section summarizes the vehicle design with a fuel cell and battery system sized to perform multiple duty cycles.

II. DUTY CYCLE DEFINITION

A. Need for real world operational data

When setting out to define an operational duty cycle for the fuel cell parcel delivery analysis, the team first consulted stock duty cycles, such as the HTUF Class 6 Parcel and Delivery truck duty cycle shown in Fig. 1 [5]. As noted by Delorme, et al., real world duty cycles can vary greatly and a single duty cycle may not reflect all demands a vehicle may see, and in many cases, the stock duty cycles have been shown to underestimate fuel consumption. Furthermore, the stock duty cycles typically used for vehicle modeling and powertrain

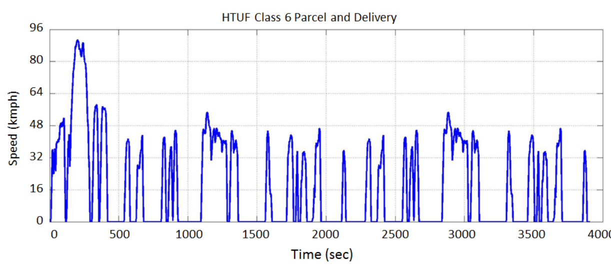

Fig. 1. HTUF Class 6 Parcel and Delivery duty cycle.

sizing do not always include grade information that can be correlated to the speed versus time profiles.

As an example of the inherent issues in not using real world route data, in examining Fig. 1, the amount of time spent at highway speeds is relatively short, accounting for approximately 3 km of distance traveled. In real world duty cycles for delivery vans, the team found that highway stretches for delivery vans routinely travel 15-30 km depending on the location of the warehouse to the neighborhoods or businesses being served. Such long periods of highway driving, with high power demands, play a significant role in balancing fuel cell power capabilities versus onboard battery energy storage needs.

The impact of the duty cycle can best be seen by the powertrain optimization sizing curve results in Fig. 2. The sizing curve shows the relationship between a given "Prime Mover" power (i.e., fuel cell in this case), and the minimum amount of onboard energy storage (i.e., battery) required to meet the route power demand. The curve is developed by selecting a prime mover size and solving for the energy storage required through an optimization routine [6]. For a given route power demand, as the prime mover size is decreased, a limit is reached where the prime mover equals the average power of the route. Anything to the right of this limit, and above the given curve will yield a charge-sustaining design, whereas anything left of this limit will result in a charge-depleting design, or not make route power demands. As shown in Fig. 2, the curves for the stock HTUF routes are well below the real world duty cycles shown as Oakland/Berkeley, Napa, Houston, and Sacramento. The results clearly point to the need for real world route data when sizing vehicular fuel cell power and battery energy storage systems.

B. Data collection and post processing

Obtaining real world route data can be achieved by GPS monitoring existing delivery vans on current routes to obtain speed profiles and route grade. Due to uncertainties with GPS accuracy and collection, significant post processing of GPS data is required to obtain route data that is suitable for vehicle route modeling [7,8]. With an accurate understanding of route conditions, previous modeling studies performed by UT-CEM show vehicle energy consumption can be estimated to accuracies within 5% [9].

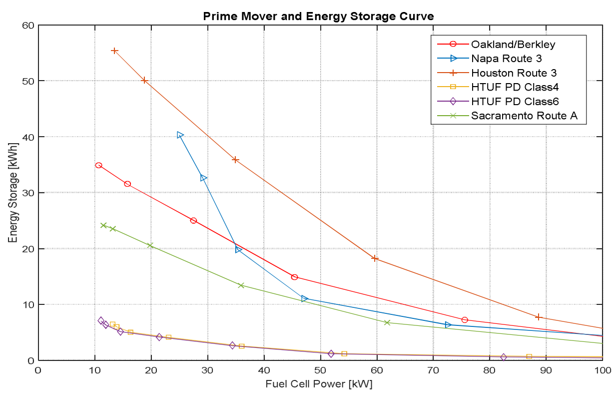

Fig. 2. Prime mover and energy storage optimization curve for a fuel cell delivery van on several routes.

To fully understand the route demands, current diesel powered UPS vehicles were equipped with commercial GPS tracking devices to collect route data during a normal day of operation. The data was recorded with a GPS device advertised with an accuracy of 2.5 m. The GPS units measured position coordinates and vehicle velocity at a constant 2 Hz rate during a 10-11 hour shift. The recorded velocity data from GPS units were used to define the time-speed profile for each of the routes. To define route elevation and grade, the SRTM1 (Shuttle Radar Topography Mission) database was used with the measured coordinate positions [10]. The accuracy of the elevation data is within 16m at 90% confidence [11].

Due to inherent uncertainties in the accuracy of the velocity measurements, GPS position data, and elevation measurements from the STRM1 database, post processing of the data is required to define a speed and grade profile that can be used to characterize the routes for modeling. The goal of this process is to smooth the data so that large and unrealistic acceleration or grade demands do not artificially drive vehicle power requirements during modeling.

To perform the data smoothing operation, a zero-phase forward and reverse 2nd order digital Butterworth IIR filter is used. For a raw data sampling frequency of 2 Hz, a low-pass cutoff frequency of 0.5 Hz is applied to the recorded speed measurements from the GPS device.

For elevation measurements, the original time base data is resampled with respect to distance at 20 m increments. This resampling process results in a distance measurement frequency of 50 samples/km. The Butterworth filtering method is applied to this dataset with a low-pass cut-off frequency of 2.5 samples/km. From the smoothed elevation dataset, the route grade, θ, is estimated by using a backwards difference method to compare elevation change, h, to distance, x.

$$\theta_n = \frac{h_n - h_{n-1}}{x_n - x_{n-1}} \tag{1}$$

Samples of the raw and smoothed speed and elevation data from a data set are shown in Fig. 3. The drastic changes in velocity of the raw data may result in over estimating the vehicle on route energy consumption and power requirements. The data smoothing operation also addresses similar concerns in the route elevation profile. In addition to uncertainty within the elevation data set, the original elevation data set may not include changes due to man-made objects such as overpasses and bridges. Although this method is a simple and low cost way to define a route, the analysts should also be aware of such inconsistencies.

C. Duty cycle chracteristics

During the study, over 10 UPS delivery routes throughout California and Houston, Texas, were recorded. This paper focuses on three routes from California and one from Houston that contrast significantly in operational duty cycle.

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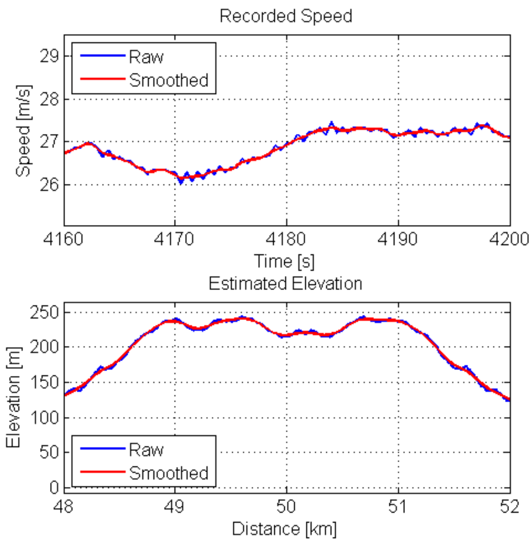

Fig. 3. Comparison of raw and filtered GPS route data.

The routes are referred to by the city or region in which they are located: (1) Oakland/Berkeley Hills, (2) Napa, (3) Sacramento, and (4) Houston. Table I summarizes several route metrics and provides a comparison of the relative demands of each route. Data for an extended HTUF Class 6 Parcel and Delivery is also included in Table I for comparison. The extended version of this route was formed by repeating the package delivery sections of the route multiple times to develop a route that was 200 km in length. As documented in Table I, the Oakland/Berkeley and Napa routes include significant grades, while Sacramento and Houston are relatively flat. Also of note, the Napa and Houston routes are longer than Oakland/Berkeley and Sacramento with higher average speeds and a lower percentage of their time stopped and delivering packages. The Napa route is the most demanding duty cycle with large highway stretches and significant grade, which drove vehicle design decisions.

TABLE I. PARCEL DELIVERY ROUTES METRICS.

Route Metric	**Parcel Delivery Routes**				
	Oakland/ Berkeley	***Napa***	***Sacramento***	***Houston***	***HTUF Class 6 PD*** [a]
Distance	103 km	199 km	80 km	164 km	201 km
Distance at grade <5%	69 km	159 km	80 km	164 km	0 km
Distance at grade >5%	34 km	40 km	0 km	0 km	0 km
Time at <1.6 kmph	71%	49%	76%	49 %	54 %
Distance at <30k mph	44 km	47 km	24 km	54 km	41 km
Distance at >80 kmph	31 km	48 km	21 km	59 km	3.7 km

a. This route repeated the package delivery section of the HTUF Class 6 PD route several times to form a 200 km long route. Highway speed sections of the HTUF Class 6 PD route were included only at the beginning and end of the route.

III. MODELING TRADE STUDY

Once target route profiles were determined, a trade study was performed to estimate vehicle performance for meeting the route demands. The detailed vehicle models were analyzed using PSAT (Powertrains System Analysis Toolkit), which is a Matlab / Simulink based modeling software and predecessor to the current package Autonomie. The vehicle was laid out as a series hybrid, where a relatively low powered fuel cell serves as a range extender for the batteries.

A. Vehicle trade study configurations and properties

The team assumes a 200 kW traction motor will power the drive train through a 2 speed transmission and rear differential, along with other general specifications for the vehicle. Values for rolling resistance are estimated from Wong [12] for bias ply truck tires. Table II shows the base vehicle parameters used in the simulations. The base vehicle curb weight includes the chassis and body and common vehicle systems and does not include the mass of the fuel cell and balance of plant, batteries, or hydrogen storage system. The hydrogen storage system mass is based on two Luxfer W205 cylinders with an additional 91 kg allotted for plumbing, mounting, and road debris protection. Finally, a key assumption in the modeling of the fuel cell vehicle design was a constant payload of 2722 kg (6000 lbs), which was determined through consultation with parcel delivery companies, which noted their vans depart fully loaded and return fully loaded with packages picked up along the route.

The design variables for the final vehicle configurations included the fuel cell power module and battery energy storage. Based on the results in Fig. 2 and the need to balance physical space constraints on the vehicle, four vehicle variants with fuel cells of 16 and 32 kW and battery energy storage of 33 and 49 kWh were evaluated. The fuel cell modules are the Hydrogenics HD16 and HD30, and the batteries are Valence $LiFeMgPO_4$ P40-24 power modules in a 2s15p or 3s15p configuration. The analysis includes vendor specifications for the fuel cell and battery systems, as well as mass allowances for packaging and balance of plant components, with the assumption that the module mass accounts for 57% of the total system mass once. Table III outlines the four vehicle variants and properties used in the simulations.

B. Simulation results

Each van configuration was simulated on all four duty cycles under consideration. In addition, the team included results for a battery electric version of the same delivery van. This van used similar Valence batteries with 99 kWh of energy storage. The total vehicle mass in this case was 7212 kg. As a first step in the analysis procedure, GPS and performance data was collected on an existing battery electric van while in operation. The team used this data to validate the models and ensure the powertrain assumptions were correct. Fig. 4 shows the energy consumption results for the battery and motor match well, providing confidence in the accuracy of the base electric delivery van powertrain model.

TABLE II. BASE VEHICLE PROPERTIES USED IN SIMULATION.

Vehicle property	*Value*
Base vehicle curb weight	5307 kg
Payload	2722 kg
Hydrogen storage system mass	436 kg
Rear axle gear ratio	6.8:1
Transmission	3:1 and 1:1
Frontal area	6.25 m^2
Coefficient of drag	0.7 Cd
Rolling radius	0.405 m
0^{th} order rolling resistance	0.006
2^{nd} order rolling resistance	4.5e-7
Auxilliary power (hotel loads)	500 W

TABLE III. DELIVERY VAN CONFIGURATIONS AND PROPERTIES.

	Fuel cell delivery van configurations			
Vehicle property	***16 kw / 33 kWh***	***16 kW / 49 kWh***	***32 kW / 33 kWh***	***32 kW / 49 kWh***
Fuel cell power rating	16 kW	16 kW	32 kW	32 kW
Battery energy capacity	33 kWh	49 kWh	33 kWh	49 kWh
Fuel cell moudule mass	65 kg	65 kg	130 kg	130 kg
Dc/dc converter mass	24 kg	24 kg	45 kg	45 kg
Total fuel cell system plus dc/dc converter system mass	155 kg	155 kg	305 kg	305 kg
Battery modules mass	495 kg	743 kg	495 kg	743 kg
Total battery system mass	863 kg	1295kg	863 kg	1295kg

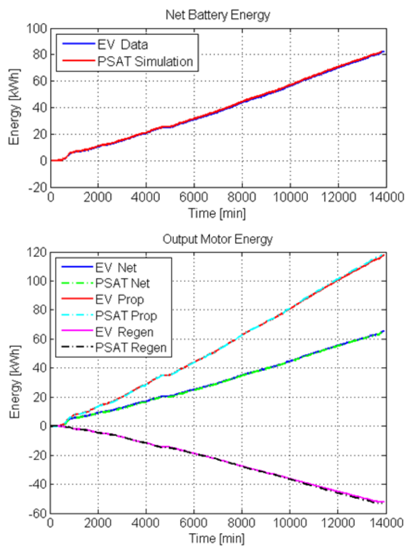

Fig. 4. Battery electric vehicle simulation validation results.

Results using the HTUF Class 6 P&D duty cycle showed that all vehicle configurations completed the route in a highly charge sustaining mode, Fig. 5 top, while the battery electric van was unable to complete the route.

Similarly for the Sacramento duty cycle, all fuel cell vehicles were able to easily complete the route, and even the battery electric van was able to complete the relatively short route with >20% state-of-charge remaining in the batteries, Fig. 5 middle.

The results became more enlightening on the more demanding duty cycles. For Oakland/Berkeley, the battery electric van's state-of-charge fell to approximately 10%, while the 16 kw / 33 kWh fuel cell hybrid configuration was unable to complete the entire route, Fig. 5 bottom.

For Napa and Houston, the route was too much for the battery electric van, Fig. 6. To complete the Napa route without discharging the batteries below 20% state-of-charge, the vehicle required the larger battery system at 49 kWh along with a 32 kW fuel cell. For the Houston duty cycle, the vehicle could complete the route with either the 16 kW or 32 kW fuel cell, as long as the battery was sized at 49 kWh. The reason for this was the long high power highway stretches during the Houston route. Although the lower power fuel cell with the larger battery was able to complete the Houston route, it should be noted that the minimum state-of-charge dipped to 20%, pointing to a need for the larger fuel cell system.

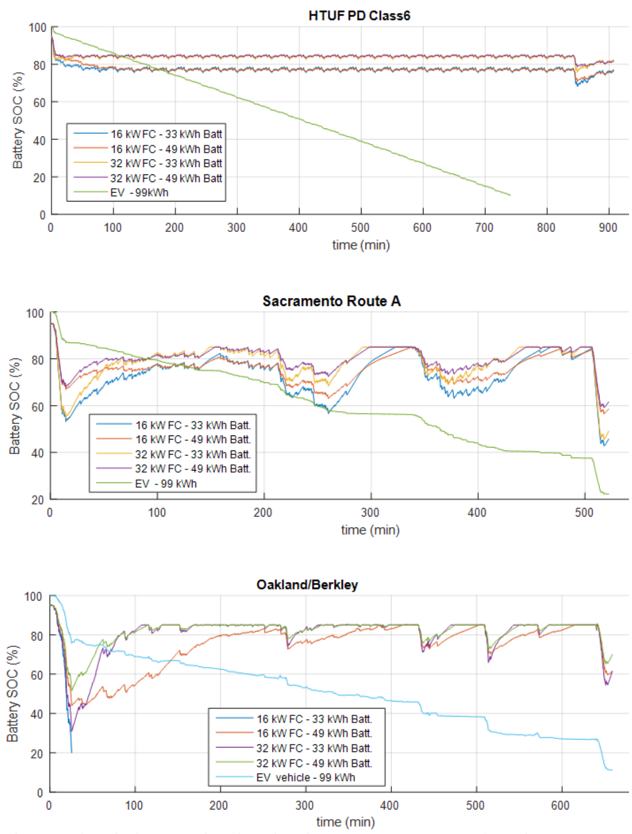

Fig. 5. Simulation results showing battery SOC versus time for HTUF Class 6, Sacramento, and Oakland / Berkeley Parcel and Delivery duty cycles.

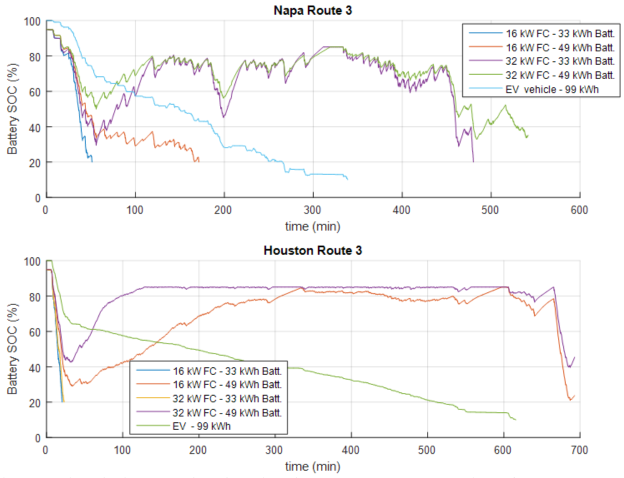

Fig. 6. Simulation results showing battery SOC versus time for Napa duty cycle (top) and Houston duty cycle (bottom).

In all simulations, the total hydrogen storage was not dictated and the vehicle was allowed to consume what was required to complete the route. The hydrogen fuel consumption varied from about 6 to 15 kg, depending on the chosen route. Table IV lists the hydrogen consumption for each vehicle and duty cycle. Instances noted as "*DNC*" mean that the particular van configuration did not complete the route.

To conclude the study, the team also conducted a thermal analysis simulation, with both free air and insulated boundary conditions, of the battery systems using the charge and discharge profiles of the batteries on the various routes. Fig. 7 shows the temperature rise in the batteries for the Napa route using a 32 kW fuel cell. The larger 49 kWh battery system had a significant thermal advantage with operating temperatures below 55°C, allowing for greater life expectancy.

As the results show, the preferred path forward for the fuel cell hybrid delivery van design is a 32 kW fuel cell power module paired with a 49 kWh battery energy storage system. This vehicle will consume 6 kg of hydrogen in light duty applications and up to 15 kg in more demanding duty cycles. Although in some cases a smaller battery system may suffice, it is likely the smaller battery system will experience degraded life with high temperature operation due to the expected high charge and discharge current profiles.

TABLE IV. HYDROGEN CONSUMPTION RESULTS.

Duty Cycle	Hydrogen Consumption (kg)			
	16 kw / 33 kWh	***16 kW / 49 kWh***	***32 kW / 33 kWh***	***32 kW / 49 kWh***
HTUF Class 6 P&D	9.96	9.96	10.02	9.92
Sacramento	6.11	5.92	6.07	5.89
Oakland / Berkeley	*DNC*	*DNC*	8.09	7.68
Napa	*DNC*	*DNC*	*DNC*	15.65
Houston	*DNC*	8.03	*DNC*	9.78

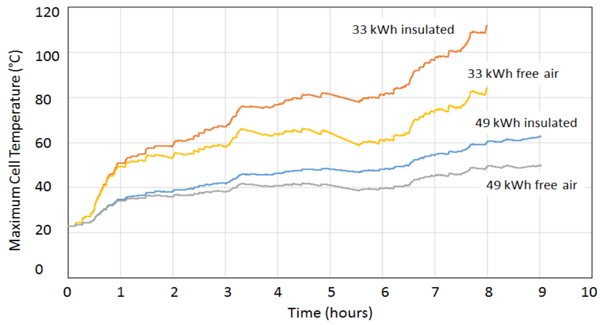

Fig. 7. Thermal simulation results for Napa route battery systems.

IV. Conclusion

This paper documents the design team's methodology for sizing the fuel cell and battery storage for converting Class 6 walk in delivery vans to hydrogen fuel cell hybrids. The most notable aspect of the design process is the development of appropriate route models using commercial GPS tracking devices to collect data on current routes and accurately represent the expected duty cycles, where high speed and high grades play a significant role in determining power and energy needs. Understanding these demands is critical in designing the vehicle powertrain. The team has concluded that a 32 kW fuel cell power system paired with a 49 kWh battery energy storage system and 15 kg of hydrogen storage will satisfy some of the most demanding parcel and delivery duty cycles and routes.

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