A Simulation Program for a Four Wheel Drive Parallel Hybrid Electric Vehicle and its Use in Rule Based Controller Development and Implementation

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Abstract

In this paper, we present a simulation model and a rule based controller design for a four wheel drive parallel hybrid electric vehicle. First, a light commercial vehicle, equipped with inherited internal combustion engine, is assembled with a battery pack, permanent magnet direct current electrical actuator and power converter. The electrical actuator capable of transforming electrical energy into mechanical energy, or in the reverse direction, converting mechanical energy into electrical energy gives the advantages of implementing energy conversion on a real-time basis under the developed rule based Hybrid Electricle Vehicle controller. The hardware and software setup is integrated into an experimental vehicle. The rule based controller and logic design is shown to reduce fuel consumption and undesired emission of internal combustion engine with the assistance of the electrical actuator in a simulation study. Regenerative braking is shownto be capable of gaining some of the mechanical energy back as reusable electrical energy within physical constraints and braking regulation limits. The designed controller and logic switching between the two actuators of the vehicle are validated by experimental results.

I. INTRODUCTION

Mass production of Hybrid Electric Vehicles (HEV) is becoming a global strategy for car manufacturers due to their prominent role in bringing down fossil fuel consumption and emissions. Hybrid vehicles are a temporary solution on the way to the zero emission road vehicle. Toyota is planning to produce all its vehicles with hybrid technology by 2012 [1] and the sales volume of hybrid electric vehicles in the U.S. is expected to increase by 268 percent between the years 2005 and 2012 according to reference [2].

The effectiveness of fuel consumption depends not only on vehicle design but also the control strategy used. There is several HEV control strategies proposed in the literature. The underlying methodology in HEV control is to find the optimum power split ratio between the two power sources. The simplest and easiest to adapt is the rule based control algorithm [3]. In this algorithm, the vehicle states are detected and the control commands are generated based on rules corresponding to the particular state. Minimization of a cost function is not used in the rule based approach. The rules are constructed based on engineering intuition and analyses of fuel consumption and emission maps belonging to the internal combustion engine (ICE), rather than analytical computation of optimum operating points. In some HEV applications, deterministic optimal control is applied (see [4]). For a given speed profile, the global optimum operation paths of vehicle components may be calculated using the dynamic programming method. However, in real driving conditions, the speed profile is not known a priori and a global minimum can not be determined. The remedy is to find sub-optimal solutions approaching the global optimum. One of these suboptimal methods is to compute equivalent fuel consumption and to evaluate power split ratio instantaneously to minimize a chosen cost function [5-8]. Another approach is to apply stochastic optimal control methods in the short time intervals while predicting the speed profile of the controlled HEV [9].

This paper discusses the modeling and control of a four wheel drive hybrid electric vehicle and experimental test results. An explanation of the model structure is given in section II. In sections III and IV, the control algorithm and hardware setup are presented, respectively. Simulation results are given in section V and experimental results are given in section VI. The paper ends with conclusions.

II. VEHICLE MODEL

In this study, a four wheel drive Ford Transit commercial van is modeled using the Matlab/SIMULINK toolbox. Since rear and front wheel drive vans were commercially available, the experimental vehicle was formed by combining these two drive axles in one vehicle. The result was a four wheel drive (4WD) hybrid electric vehicle. The front drive is powered by the internal combustion engine and the rear drive is powered by

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the electric motor. A first prototype HEV of this construction was explained in our previous work in [3]. This paper concentrates on a second prototype vehicle, referred to as experimental vehicle hereafter, based on this 4WD concept.

Modeling of this experimental vehicle is presented first. The equations of dynamics for the model were presented in reference [3] and will not be repeated here. The Simulink implementation of the model is shown in Fig. 1. This model consists of six individual blocks. These blocks are the longitudinal vehicle model, tire model, internal combustion engine model, electric motor model, driver model and supervisory controller model.

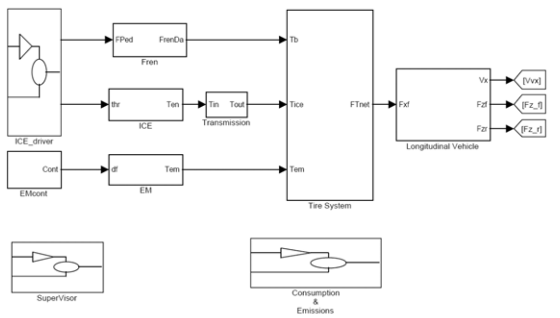

Fig. 1. Simulink vehicle model

The net force is used to compute vehicle acceleration by subtracting the resistance forces such as aerodynamic, rolling resistances and the resistance induced by road slope, from the traction forces that are available from the tire blocks. The Pajecka 2002 tire equations are used for modeling the tire. Although the tire model is capable of computing all tire forces and moments, only longitudinal forces are utilized here. The lateral forces and moments can be used for further studies such as hybrid vehicle lateral stability analysis due to the fact that the established model is modular in structure.

The engine is modeled using engine maps that give the output engine torque for the two inputs of engine speed and accelerator pedal position. Transient regimes of the engine are thus not treated. Negative engine torques are computed as a function of cylinder head temperature and engine speed.

Transmission components are assumed to be rigid bodies and only equivalent inertias and transmission ratios are used to model the driveline. Even though the efficiency of transmission components varies with respect to transmission speed, gear ratio and the torque, constant efficiency values are used for simplification.

For a given speed profile, the driver model is input the desired speed and actual speed. Anti-windup Proportional-Integral (PI) controllers are used to model the driver and to command the ICE and EM. Two feedback options are available in this case. Speed feedback is not suitable for controlling the 4WD vehicle since the rear and front axle dynamics require different torques due to the different component properties. Thus, torque feedback should be used in order to follow the desired speed profile. Once the desired speed starts to increase, the controller sends the throttle signal to the engine. Additionally, the driver model generates clutch and brake signals. To imitate the real clutch-engine relation for the electric motor only state, and to improve driving feeling while shifting gears with respect to conventional ICE vans, a potentiometer that generates a linear signal between “0” and “1” is used in the experimental vehicle.

Tables including data of braking torque versus brake pedal position are used for modeling the brakes. In order not to change braking characteristics of the vehicle, a force gap is allocated for regenerative braking. Along this gap, only regenerative braking is allowed. In designing regenerative braking, the regulations on braking are also noted. After a certain amount of applied pedal force, conventional friction brakes are activated and the regenerative braking torque is decreased gradually as seen in Fig. 2.

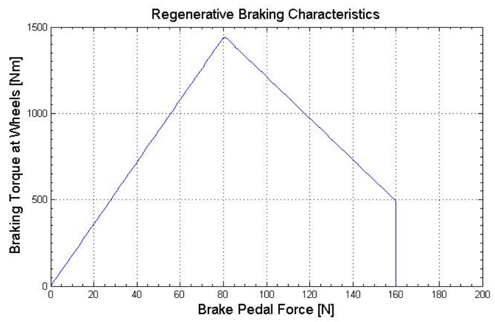

Fig. 2. Regenerative braking characteristics

A simple equivalent circuit is used as the battery model. The open circuit voltage and internal resistance depending on state of charge and current flow direction are used to build the necessary equations. For simplification of the overall electric traction system modeling, a permanent magnet direct current motor model is used [3].

III. RULES AND FINE TUNING

The main aim in rule based control is to operate the ICE at high loads which correspond to its efficient regions. For this reason, the electric motor (EM) only mode operates under a predetermined driver power request and in assist modes. The required power to drive the vehicle is computed for a given drive cycle. In real conditions, driver power or torque request at the wheels should be computed by evaluating the accelerator pedal position and brake pedal force. Measured values are used in the ICE torque and brake maps and the positive or negative desired torques are calculated.

Table I. Transition Logic

	Vx	SOC	Prequest	Tice_max	Tem_max	Fbrake
Standstill	< 5 km/h	--	--	--	--	--
Pure EM	--	> SOClow	< 6 kW	--	< Treq	--
Pure ICE	--	< SOClow	< 6 kW	--	--	--
Pure ICE	--	> SOClow	> 7 kW	> Treq	--	--
EM Assist	--	> SOClow	--	< Treq	--	--
EM Generator	--	< SOClow	--	< Treq+Tchg	< Tchg	--
Regen. Braking	--	< SOChigh	--	--	--	< 80
Conv. Braking	--	>= SOChigh	--	--	--	--
Conv. Braking	--	< SOChigh	--	--	--	> 90

There are five main vehicle states in the control algorithm which are (see Fig. 3).

- Standstill vehicle position (Standstill mode)
- Pure EM excitation (EM mode)
- Pure ICE excitation (ICE mode)
- Charging or EM assist (Hybrid mode)
- Braking mode (regenerative and conventional friction braking)

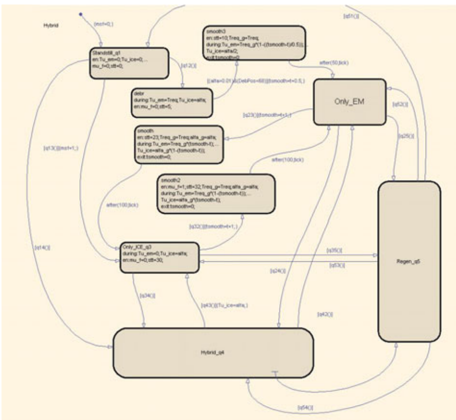

Fig. 3. Vehicle states

To decide which state will be active, some transition rules are used. If the vehicle speed is below a small value such as 5 km/h, the vehicle is assumed to be in standstill position. Other state transitions are determined according to the logic rules given Table I. To avoid limit cycle oscillations, hystereses are added to the transitions.

Traction torque is supplied by the electric motor in the pure EM mode, and the ICE follows the wheel speed. The engine compression brake becomes active as shown in Fig. 4. since the manual clutch can not be commanded automatically. This is a drawback of the experimental vehicle as the EM should meet both the driver request and engine compression brake during the EM only mode. This drawback is compensated since the engine cuts off fuel while braking.

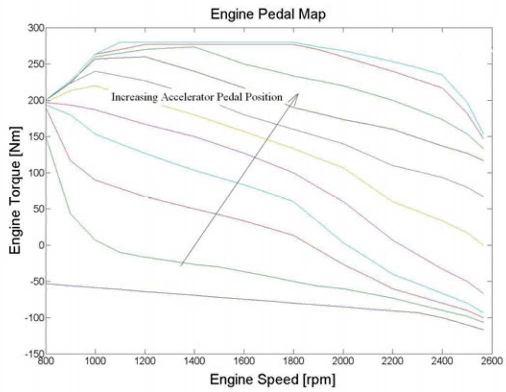

Fig. 4. Engine torque map

Another difficulty is to keep drivability of the hybrid electric vehicle at the same level as the conventional vehicle in the presence of a manual clutch. This can be compensated by using appropriate transition functions between pure ICE and pure EM states and by using the clutch potentiometer to sense clutch position.

The transition function is a function of the torque supplied by the power source at the wheels and time. If the transition conditions are realized between ICE and EM, the vehicle enters the transition states (Fig 5.).

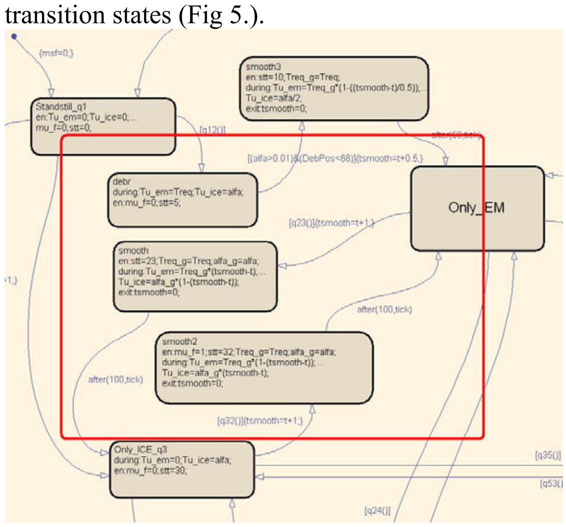

Fig. 5. Transition states

During the transition states, the instantaneous required torque at the wheels is supplied by both power sources. For instance the EM power starts to decrease linearly as the ICE power increases linearly to keep supplying the required power (Fig. 6.).

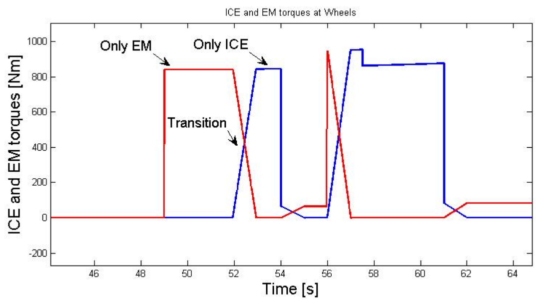

Fig. 6. EM and ICE torques in transition states

The driver does not feel the transition, since the total torque always equal the demanded torque. To avoid unwanted oscillations such as shunt and shuffle during the transitions, the demanded torque, engine torque and EM torque at the wheels should be computed accurately. This is obviously an open loop control approach. If an accurate engine map, i.e., torque output versus ICE speed, is available, an inverse map can be used to distribute required torque between the EM and the ICE. Another easier approach is to calibrate the accelerator pedal position in such a way that the EM generates the same amount of torque as the ICE for the same pedal position [3].

The current transmission gear ratio should also be estimated real time in order to compute the torque demand at the wheels. Vehicle speed and wheel angular speeds are available on the CAN bus. The ratio of these two speeds gives the transmission gear ratio and thus the stick shift position. There are upper and lower variations for each gear ratio as shown in Fig. 7. The gear position estimation is carried out using a Stateflow diagram in Simulink.

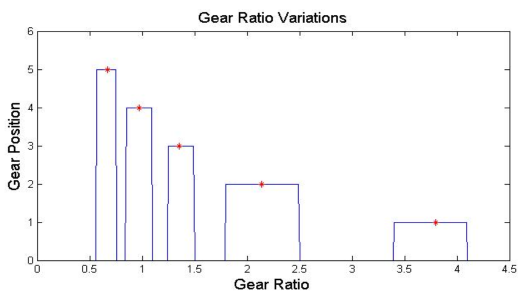

Fig. 7. Gear ratio variations

IV. HARDWARE SETUP

A dSpace MicroAutoBox (MABX) complemented with a RapidPro system was used as the main electronic control unit to run the hybrid electric vehicle control algorithm. The MABX and Rapidpro system installed in the Ford Transit van is shown in Fig. 8.

All signals required by the HEV controller were gathered via the MABX and the RapidPro signal conditioning units. Vehicle and battery states are monitored via CAN, the other signals are analog. The general signal connection diagram is shown in Fig. 9. The HEV control strategy is modeled in Matlab/Simulink. Automatic code generation and downloading into MABX is handled by the Matlab Real Time Workshop and dSpace Real Time Interface tools as illustrated in Fig. 10.

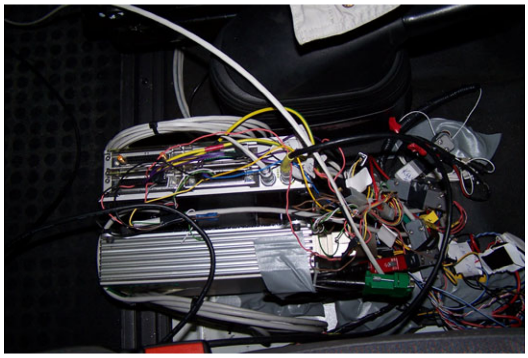

Fig. 8. HEV controller hardware connections in the experimental vehicle

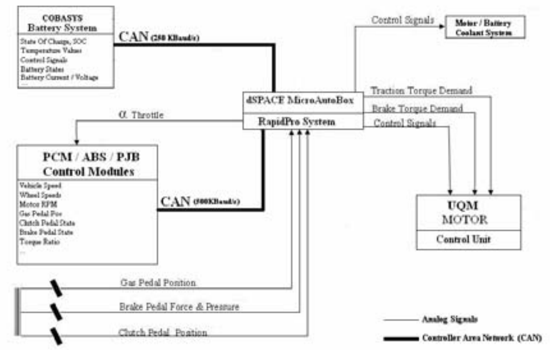

Fig. 9. General signal connection diagram

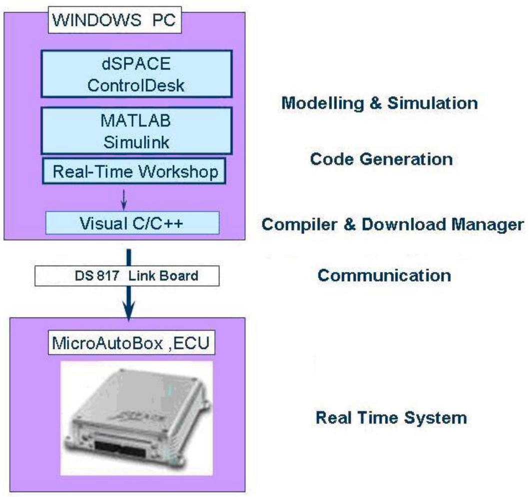

Fig. 10. Rapid HEV control algorithm prototyping process diagram

As seen in Fig. 11, the EM driver enables the conversion of DC voltage to AC voltage. The electric power is supplied by a battery pack which is connected to the motor driver through a circuit breaker as a safety switch. The available EM driver control signals (enable, direction, acceleration, brake) allow smooth operation of the EM via its driver. The HEV control unit sends the commands to the controller as acceleration or brake requests. The EM driver applies these requests according to the motor operating region or generator operating region maps [3].

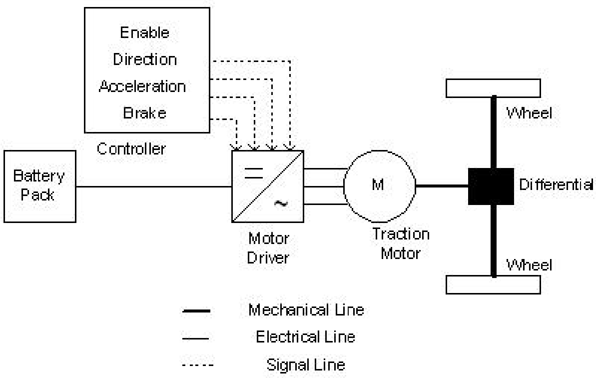

Fig. 11. EM electrical and mechanical connections [3]

V. SIMULATION RESULTS WITH POWER ORIENTED CONTROL RULES

The EUDC drive cycle was used in simulation to compute fuel consumption and emitted emission quantities. The results are listed in Table II for a vehicle mass of 3000 kg. Emission values given in Table II are the engine-out emissions. SOC is short for state of charge of the batteries.

Table II. Fuel Consumption and Emissions

	Conven.	Hybrid	Improv.
Fuel Consump.	11 litre/100 km	9.3 litre/100 km	% 15.5
Change in SOC	--	% 0	--
NO_x	0.77 gr/km	0.55 gr/km	% 28
CO_2	2.76 gr/km	2.26 gr/km	% 18
CO	5 gr/km	4.75 gr/km	% 5

Acceleration tests were also performed. For this reason, a gear shift algorithm pertaining to this vehicle is necessary. To determine the gear up shift points, the torque versus engine speed curves at the wheels were drawn for each gear (Fig. 12). The intersection of the curves are the gear shift points that maximize the area and thus acceleration performance under these curves. If this is repeated for each accelerator position with a specified increment, the gear shift graph in Fig. 13 is obtained.

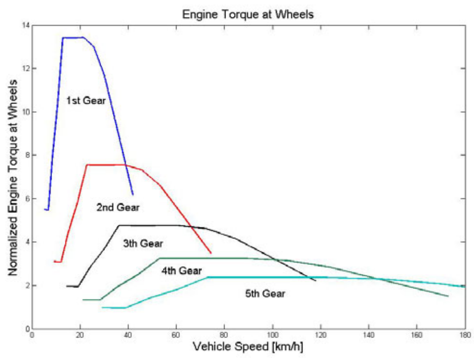

Fig 12. Engine torque versus vehicle speed

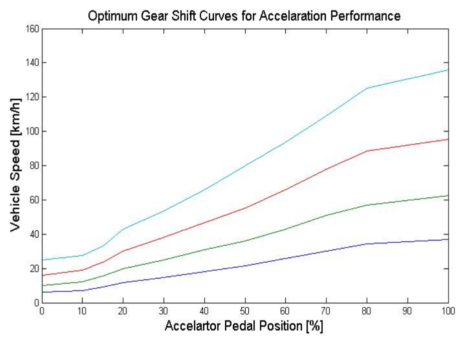

Fig. 13. Optimal gear shift curves for acceleration performance

In hybrid acceleration tests, the EM operates in the assist mode according to the rule based control algorithm. If the pedal opening exceeds %70 of its full travel range, the EM starts to give assist torque linearly.

Acceleration simulation results are given table III and Figures 14-15.

Table III. Conventional and Hybrid vehicles acceleration performance

	Conventional [s]	Hybrid [s]
8-32,3 km/h	2,086	2,08
8-56,4 km/h	5,6	5.6
0-100 km/h	22,37	17,13
80-120 km/h	18,76	6,61

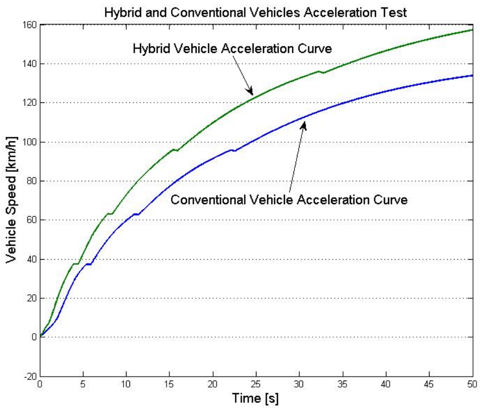

Fig 14. Simulated Hybrid and Conventional vehicles acceleration performances

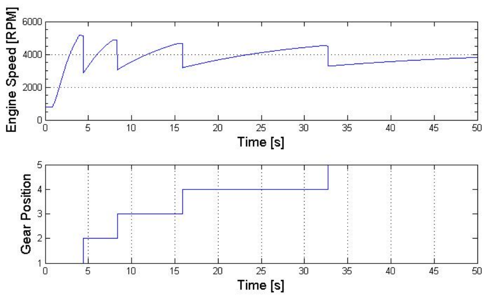

Fig 15. Simulated engine speed and gear positon history

VI. EXPERIMENTAL RESULTS AND MODEL VERIFICATION

Accelerator, brake, clutch pedal and gear positions were recorded during an experimental acceleration test and were used as inputs to the simulation model in a subsequent simulation study.

The experimantal and simulation results are displayed in Figures 16 and 17. The simulated and real test results are observed to be very close to each other. The HEV control algorithm states entered in acceleration tests are shown in Fig. 18.

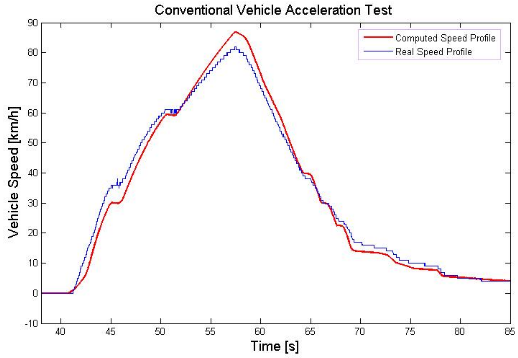

Fig 16. Conventional vehicle acceleration comparison of simulated and experimental responses

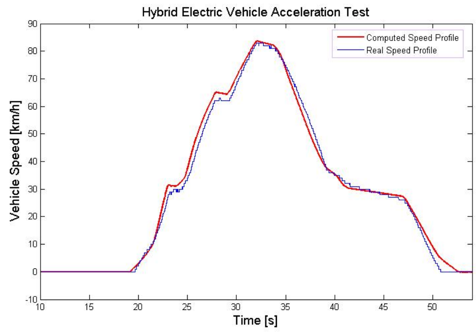

Fig 17. Hybrid vehicle acceleration comparison simulated and experimental responses

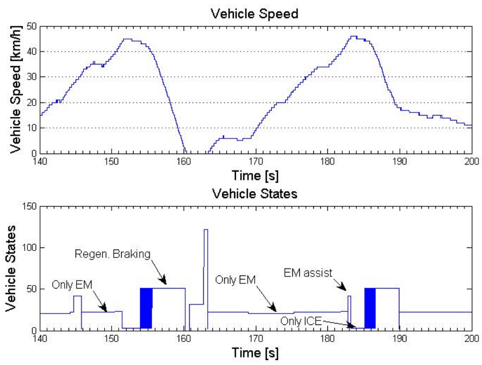

Fig 18. Vehicle speed and states during test drive

During driving tests, the state of charge of the vehicle was also recorded as shown in Fig. 19. In the charge state, the torque request of the driver is evaluated and a charge torque is calculated within component constraints. Since the ICE meets both the driver torque demand and the charge torque in the charge mode, the driver does not feel a significant change with respect to the conventional vehicle.

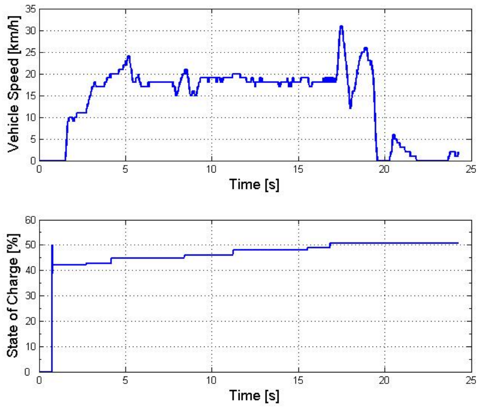

Fig 19. SOC change in Charge state

VII. CONCLUSIONS

Two vehicles were successively converted into hybrid electric vehicles and instrumented with a battery, an electric motor and sensors. The second experimental vehicle is shown in Fig. 20. A simulation model and its use in designing a rule based control algorithm were presented. Simulation and experimental results were compared to demonstrate the validity of the results achieved. Future work will concentrate on the use of local and global optimization methods.

Fig. 20 Ford Transit Van and battery packs

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