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An Efficient Methodology Proposed For Deciding About the Number of Battery Modules In Hybrid Electric Vehicles

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Original scientific paper

Selection of higher values for Degree of Hybridization (DOH) increases the fuel economy and reduces the emissions in the Hybrid Electric Vehicles (HEVs). Previously presented methodologies for deciding about the number of battery modules (as an important factor influencing the vehicle performance), presents poor vehicle performance for higher DOHs. In this paper, a new technique has been proposed for deciding about the number of battery modules in Hybrid Electric Vehicles (HEVs), by which the high performance of the vehicle is guaranteed for higher DOHs. The proposed methodology is based on satisfying two key designing factors: Maximum charge and discharge capability and satisfaction of the PNGV criteria. The proposed methodology, allows us to choose higher DOHs in HEVs, which leads to lower emissions and higher levels of fuel economy. To evaluate efficiency of proposed methodology, it has been applied on model of a test parallel passenger hybrid car available in the ADvanced VehIcle SimulatOR (ADVISOR) software. The obtained results have been compared with that of formerly presented techniques. Simulation results confirm the effectiveness of proposed methodology.

Key words: Battery Modules, Charge and Discharge Capability, Hybrid Electric Vehicle, PNGV Criteria

Učinkoviti pristup odabira broja baterijskih modula kod hibridnih električnih vozila. Povećanje stupnja hibridizacije (DOH) ima za posljedicu smanjenje potrošnje goriva te emisije štetnih plinova kod hibridnih električnih vozila (HEV). Postojeći pristupi za odabir broja baterijskih modula (kao važan faktor koji utječe na performanse vozila) kod većeg stupnja DOH-a rezultiraju lošim performansama vozila. U ovom radu, predložen je novi pristup odabira broja baterijskih modula HEV-a, koji garantira visoke performanse HEV-a i za visok stupanj DOH-a. Predloženi pristup temeljen je na zadovoljavanju dva ključna zahtjeva: maksimalna sposobnost punjenja i pražnjenja te PNGV kriterij. Predložen pristup omogućuje odabir visokog stupnja DOH-a u hibridnim električnim vozilima. Pristup je validiran korištenjem modela hibridnog automobila dostupnog u ADvanced VehIcle SimulatoOR programu. Dobiveni rezultati uspoređeni su s rezultatima trenutno korištenih pritupa odabira broja baterijskih modula te je potvrđena učinkovitost predloženog pristupa.

Ključne riječi: baterijski moduli, sposobnost punjenja i pražnjenja, hibridno električno vozilo, PNGV kriterij

1 INTRODUCTION

In recent years, several methods have been proposed for deciding about the number of battery modules in hybrid electric vehicles. In [1-4] minimum number of battery modules that is needed for covering the desired driving cycle, has been chosen as the number of battery modules. That is why this simple methodology is usually called as "minimum number of battery modules". Applying this methodology, results in lightness of vehicle due to lower number of battery modules that are used (advantage of this methodology), but at the same time it leads to poor vehicle performance (disadvantage of this methodology). In [5-9] power matching strategy has been used for deciding about the number of battery modules. In this technique, energy storage system has to be capable of supplying any power needed by electric motor. Maximum amount of power that may be needed by the electric motor is its rated value. So, rated power of the electric motor determines suitable number of battery modules. This methodology makes vehicle heavier (than that of former mentioned methodology), but leads to better vehicle performance. Also, we can find several other techniques in [10-13].

In this paper a new methodology is introduced that guarantees high performance of vehicle, maximizes amount of energy absorbed by energy storage system during regenerative braking conditions and makes it possible to choose higher Degrees of Hybridization which leads to lower emissions and higher levels of fuel economy. In parallel hybrid electric vehicles, Degree of Hybridization (DOH) is usually defined as equation (1) [2, 5, 7-9, 14-19].

$$DOH = \frac{P_{EM}}{P_{EM} + P_{ICE}} = \frac{P_{EM}}{P_{Total}}. \quad (1)$$

Where, $\mathrm{P_{EM}}$ is the rated power of electric motor, $\mathrm{P_{ICE}}$represents the rated power of internal combustion engine and $\mathrm{P_{Total}}$ is the total power of the HEV which is sum of $\mathrm{P_{EM}}$ and $\mathrm{P_{ICE}}$.

2 PROPOSED METHODOLOGY

In this methodology, suitable number of battery modules is decided based on maximizing charge and discharge capability of energy storage system and at the same time, satisfying Partnership for New Generation of Vehicles (PNGV) criteria [7, 20]. These two designing factors are described in the following section.

2.1 Maximum charge and discharge capability

The energy storage system of hybrid electric vehicles should always be able to produce the power needed by the electric motor. Maximum amount of propulsion power that can be requested during a driving cycle from the electric motor is its rated power. So, maximum amount of power production that the energy storage system should be capable is [19]:

$$Maximum\ discharge\ power\ = \frac{P_{EM}}{\eta_{Converter}}. \quad (2)$$

Where, $\mathrm{P_{EM}}$ as mentioned before, is the rated power of the electric motor and $\eta_{\mathrm{Converter}}$represents overall efficiency of the converters used between the energy storage system and electric motor, and the electric motor also. On the other hand, energy storage system (battery pack) must be able to absorb the total regenerative power of wheels, during the regenerative braking conditions. Maximum charging power of energy storage system during the regenerative braking conditions can be calculated from (3) [19]:

$$Maximum\ charge\ power\ = P_{EM} \times \eta_{Converter}. \quad (3)$$

Therefore, the number of battery modules must be decided in a way that the energy storage system be capable of providing as much as "maximum discharge power" and storing as much as "maximum charge power".

2.2 Satisfaction of PNGV (Partnership for New Generation of Vehicles) criteria

In 1993, the United States Government and the Chief Executive Officers of the three major domestic automakers announced the Partnership for A New Generation of Vehicles (PNGV). PNGV is a cooperative research effort to develop automobiles with very low emissions, safe, attractive performance, and affordable prices that get up to three times the fuel efficiency of conventional vehicles sold today. During recent years, Partnership for New Generation of Vehicles (PNGV) organization has introduced some measures in order to guarantee the high performance of newly designed hybrid electric vehicles [7, 20]. These measures are as follows:

1. 0-60 mph acceleration time must be equal or lower than 12 seconds.
2. 40-60 mph acceleration time must be equal or lower than 5.3 seconds.
3. 0-85 mph acceleration time must be equal or lower than 23.4 seconds.
4. Distance covered in 5 seconds must be at least 140 ft.
5. Maximum speed must be at least 90 mph.
6. Gradeability must be at least 6.5% at 55 mph and 272 kg additional weight for 1200 seconds with $\Delta\mathrm{SoC}\leq 0.05$.

The last item (6) which is about gradeability of the hybrid electric vehicles has not been considered in this study. ADvanced VehIcle SimulatOR (ADVISOR) software has been used as the simulation tool, by which the satisfaction of each PNGV criteria is checked [21-22].

3 BATTERY TYPE AND CONTROL STRATEGY

3.1 Battery type

There are many battery types with different characteristics available in the industry. Due to the frequent charge and discharge process in HEVs, the batteries have short life time. Therefore, the old battery must be replaced by new one frequently, which increase the cost. In recent years, a new technology called "Desulfation" has been presented for restoring Lead-Acid battery types. The presented technique removes the sulfate deposits from Lead-Acid battery plates, and consequently extends the battery life time, which leads to reduction of cost. Owing to the mentioned advantage, the Lead-Acid battery type with maximum capacity of 25 ah has been considered as the energy storage system for the modeled hybrid car. The battery has been modeled as an equivalent circuit with an internal resistance $\mathrm{R_{batt}}$, as shown in Fig. 1 [22].

The open circuit voltage $\mathrm{V_{OC}}$ and $\mathrm{R_{batt}}$ are both functions of the battery's State of Charge (*SOC*) and temperature. The battery temperature is assumed to be constant ($22^\circ\ C$) and the temperature effect is ignored. Instantaneous charge and discharge powers of this battery type

Table 1. Brief description of variables used in the control strategy

cs_hi_soc	highest desired battery state of charge	0.8
cs_lo_soc	lowest desired battery state of charge	0.3
$cs\_electric\_launch\_spd\_hi$	vehicle speed below which vehicle operates as a zero emissions vehicle (when $SOC > cs\_hi\_soc$)	26.8 m/s
$cs\_electric\_launch\_spd\_lo$	vehicle speed below which vehicle operates as a zero emissions vehicle (when $sc\_lo\_soc < SOC < cs\_hi\_soc$)	8 m/s
$cs\_off\_trq\_frac$	$(cs\_off\_trq\_frac) \times$ (torque capability of engine at current speed) $=$ Off Torque Envelope Minimum torque threshold, when commanded at a lower torque, the engine will shut off if $SOC > cs\_lo\_soc$	0.6
$cs\_min\_trq\_frac$	$(cs\_min\_trq\_frac) \times$ (torque capability of engine at current speed) $=$ Minimum Torque Envelope Minimum torque threshold, when commanded at a lower torque, the engine will operate at the threshold torque and the motor act as a generator, if $SOC < cs\_lo\_soc$	0.8

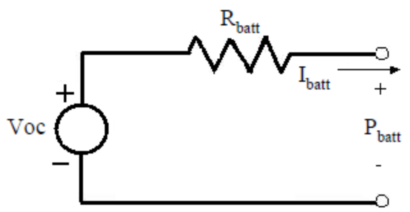

Fig. 1. Battery model

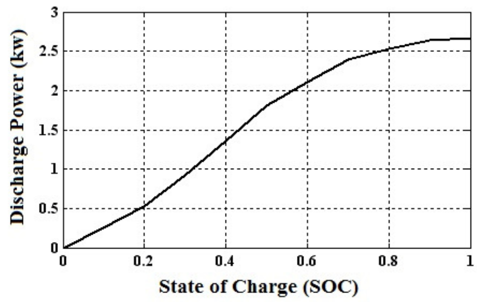

Fig. 2. Instantaneous Discharge Power vs. SOC

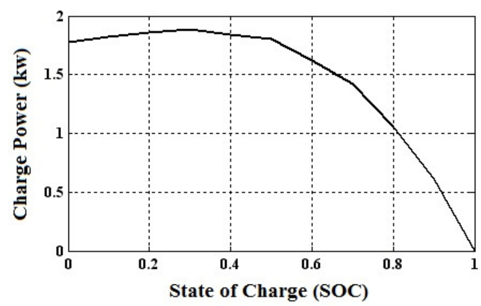

Fig. 3. Instantaneous Charge Power vs. SOC

have been shown in Fig. 2. The data of diagram of *SOC* for the applied battery have been gathered from standard experimental implementations which have been included in the ADVISOR software. Mass and nominal voltage of each battery module are 11 kg and 12 V, respectively.

3.2 Control strategy

In this study, electric assist control strategy has been used for controlling the test vehicle. In this strategy, the internal combustion engine provides the base load power (which is almost constant) and the electric motor produces the additional power needed by vehicle and maintains the charge in the batteries. The main advantage of electric assist control strategy is that it prevents the propulsion power system from low efficiency operation. This strategy uses electric motor for producing additional power needed by vehicle and maintaining charge in the batteries. Variety of conditions that electric motor is used by this control strategy is as follows [21-22].

(1) The motor can be used for all driving torque below a certain minimum vehicle speed. (2) The motor is used for torque assist if the required torque is greater than the maximum producible by the engine at the engine's operating speed. (3) The motor charges the batteries by regenerative braking. (4) When the engine would run inefficiently at the required engine torque at a given speed, the engine will shut off and the motor will produce the required torque. (5) When the Battery State of Charge (*SOC*) is low, the engine will provide excess torque which will be used by the motor to charge the battery. Brief description of control variables, have been shown in Table 1. Figures 4 and 5 illustrates the control strategy and Internal Combustion Engine (ICE) operation modes. When $SOC < cs\_lo\_soc$ (Figure 5) additional torque is required from the engine to charge the battery pack. This additional charging torque is proportional to the difference between *SOC* and average of cs_hi_soc and cs_lo_soc. This engine torque is prevented

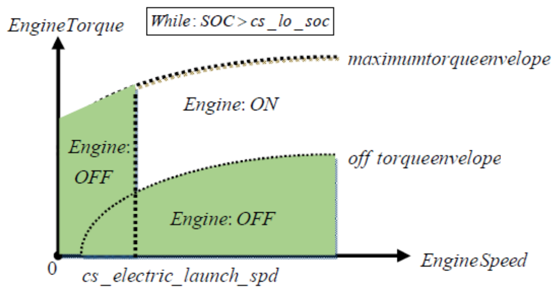

Fig. 4. Engine operation mode when SOC $>$ cs_lo_soc

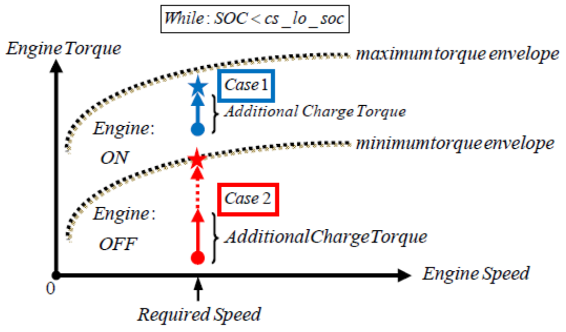

Fig. 5. Engine operation mode when SOC $<$ cs_lo_soc

from being below a certain fraction of maximum engine torque ($cs\_min\_trq\_frac$) at the current operating speed (Minimum Torque Envelope) [19-20].

4 VEHICLE DEFINITION

In this paper we have classified the cars according to their total propulsion power, not the size or mass. Based on this assumption, the cars are grouped into three small, medium (mid-size) and large classes. The cars with the total propulsion power lower than 100 kW are called small. Medium cars are the ones that their total propulsion power lies in the [100 KW-200 kW] interval. The cars with the propulsion power higher than 200 KW, are called large. In this study, a small size parallel passenger hybrid car has been modeled and used, as the test vehicle, for conducting simulations.

All the vehicle parameters have been taken from models provided in the ADVISOR software, which have been gathered from real experimental implementations. Vehicle and propulsion parameters have been shown in Tables 2 and 3, respectively [21-22].

As Table 3 shows, rated powers of used electric motor and internal combustion engine (ICE) are 31 kW and 63 kW, respectively. So, total power of the test vehicle is considered to be 94 kW. It is assumed that this total power is constant during the simulations. Table 4 also, elaborates different components that have been used for modeling the test vehicle in ADVISOR software.

Table 2. Vehicle parameters

Parameter	**Value**
Coefficient of Drag	0.3
Vehicle Frontal Area [m^2]	1.746
Vehicle Wheelbase [m]	2.55
Vehicle Glider Mass [kg]	918
Vehicle Cargo mass [kg]	136
Wheel Radius [m]	0.282
Air Density [kg/m^3]	1.2
Coefficient of Rolling Resistance	0.009

Table 3. Propulsion parameters

Internal Combustion Engine (ICE)	Manufacture	-
	Type	Saturn 1.9*L* SOHC SI
	Max.Power	63 kW
	Peak Efficiency	0.34
Electric Motor (EM)	Manufacture	Toyota Prius
	Type	Permanent Magnet
	Max.Power	31 kW
	Mass	57 kg
	Peak Efficiency	0.91

Table 4. Components used for modelling the vehicle in ADVISOR

Component Name	**Model**
Fuel Converter	FC_SI63_emis
Electric Motor	MC_PRIUS_JPN
Exhaust After-treatment	EX_SI
Transmission	TX_5SPD
Wheel/Axle	WH_SMCAR
Power Train Control	PTC_PAR_CD
Energy Storage System	ESS_PB25

A combination of UDDS (Urban Dynamometer Driving Schedule) and HWFET (High Way Fuel Economy Test) has been used as the driving cycle in the simulations, which has been shown in Fig. 6.

5 SIMULATION SPECIFICATIONS

In order to evaluate efficiency of proposed methodology, it is applied to a small size parallel passenger hybrid car. Vehicle mass, performance, emissions and fuel economy are selected as target parameters to be monitored during simulations. It is assumed that, vehicle performance is represented by distance covered in 5 seconds, 0-60, 40-60, 0-85 mph acceleration times, gradeability and maximum

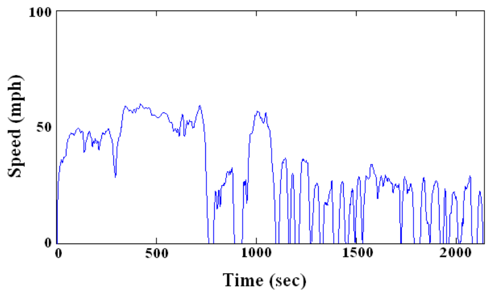

Fig. 6. Combined driving cycle (UDDS+HWFET)

speed. Brief description of simulation methodology comes in the following.

Step 1: Total power of the test vehicle is kept constant and the DOH is altered within its valid range by increment steps of 0.05.

Step 2: For each DOH, number of battery modules is calculated applying each of newly and previously proposed methodologies (minimum number of battery modules as first method, power matching as second method and newly proposed methodology as third method).

Step 3: For each DOH, corresponding value of target parameters are extracted from ADVISOR software.

Step 4: Comparing the results obtained for each methodology, most efficient methodology is introduced.

6 SIMULATION RESULTS

As mentioned before, total power of the test vehicle is assumed to be 94 kW. Since for $DOH < 0.3$, the electric motor and for $DOH > 0.65$ the ICE, are not capable of providing needed power, valid range of DOH for first methodology (minimum number of battery modules) is [0.3-0.65]. For the same reason, the valid range of DOH for second methodology is [0.45-0.65]. In third methodology, the electric motor is not capable of providing needed power for $DOH < 0.35$. Also for $DOH > 0.55$, it is not possible to satisfy all the PNGV criteria simultaneously. So, the valid range for DOH, while using the new proposed methodology (third methodology) is [0.35-0.55].

Simulation methodology, described in previous section has been applied on each of newly and previously presented methodologies. Obtained results have been shown in Tables 5-7. Figure 7 and 8, respectively show the number of battery modules and vehicle mass calculated by each of newly and previously proposed methodologies, for each DOH.

Figure 7 shows that for lower DOHs, almost the same number of battery modules is calculated by each of three methods, but for higher DOHs, number of battery modules calculated by third method (proposed methodology) is

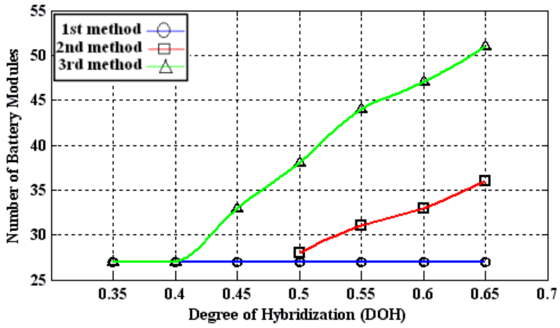

Fig. 7. Number of battery modules for each DOH

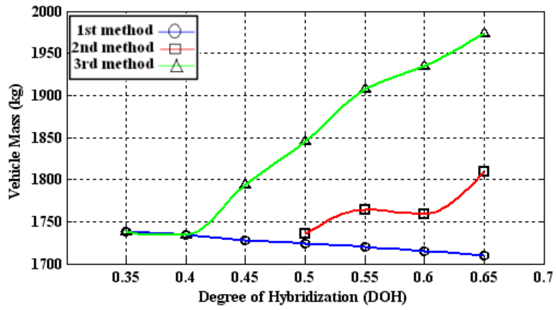

Fig. 8. Vehicle mass vs. DOH

much higher than other two methods, because higher number of battery modules is needed to satisfy PNGV criteria. Higher number of battery modules, calculated by third method (proposed methodology), makes the car heavy and huge. Heaviness and hugeness of the vehicle are the main disadvantages of the proposed methodology. Figure 9 shows the fuel economy of the test vehicle, obtained by each of three methods. All the three methods have almost the same effect on the fuel economy of the car. Also, it can be seen that higher degrees of hybridizations (DOHs), results in higher levels of fuel economy. Figure 10 illustrates the variation of emissions versus different DOHs. Variation pattern of emissions for all the three methods are the same. Choosing higher DOHs, leads to lower levels of vehicle emissions. In this study, Emissions of the vehicle has been defined as (4).

$$\text{Emissions} = \frac{[HC + CO + NO_x]}{3}. \tag{4}$$

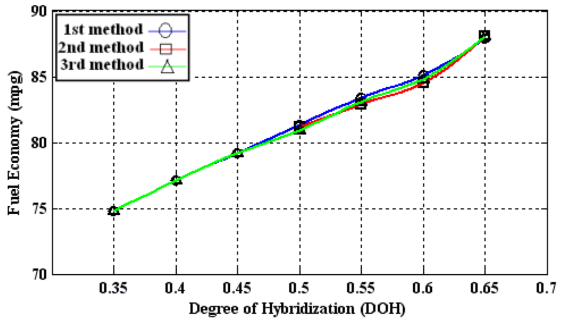

Fig. 9. Fuel economy vs. DOH

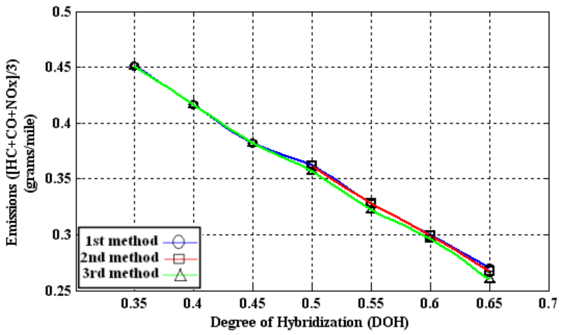

Fig. 10. Emissions vs. DOH

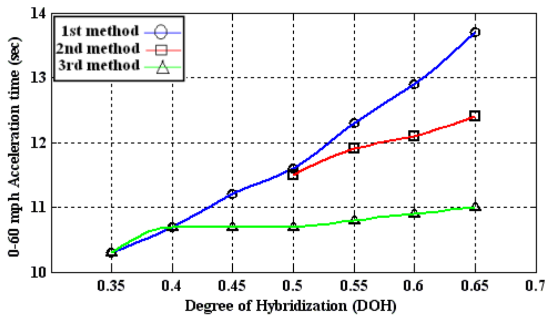

Fig. 11. 0-60 mph Acceleration times vs. DOH

Figures 11 to 13 show the 0-60, 40-60 and 0-85 mph acceleration times of the car, respectively. While using first and second methods, the acceleration times begin to increase dramatically as the DOH increases, but when the third method (proposed methodology) is used, these acceleration times remain within the limits assigned by PNGV. This satisfaction of PNGV criteria, guarantees high performance of the vehicle. For DOHs higher than 0.55 it is not possible to keep the 40-60 acceleration time within the limits of PNGV. That is why we haven't plotted this interval, in figure 12.

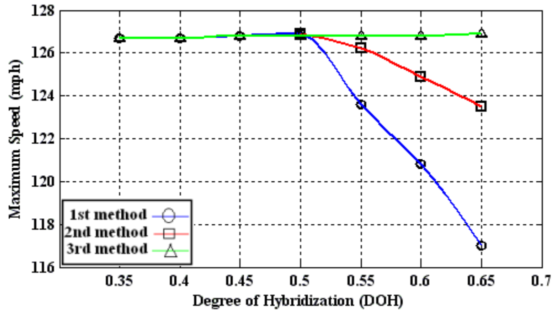

Fig. 14. Maximum speed vs. DOH

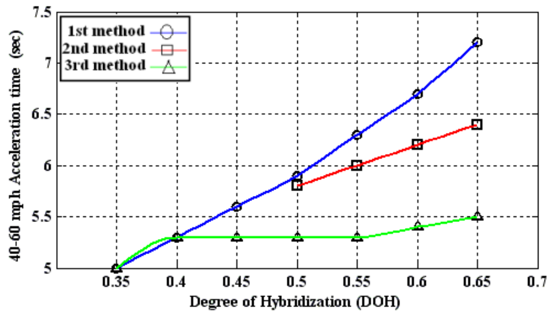

Fig. 12. 40-60 mph Acceleration times vs. DOH

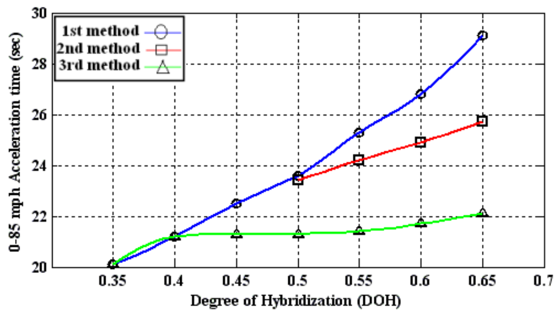

Fig. 13. 0-85 mph Acceleration times vs. DOH

Maximum speed of the test vehicle has been shown in figure 14. While using first and second methods, as DOH increases, maximum speed of the vehicle stays nearly unchanged till DOH=0.5. If we still keep on increasing the DOH beyond the 0.5, maximum speed of vehicle will start to decrease dramatically, which leads to poor vehicle performance. If the proposed methodology (third method) be applied, maximum speed will remain over 126 mph, which helps to have better vehicle performance.

Figure 15 illustrates how gradeability of the test vehicle changes with alteration of the DOH. As the DOH increases, Gradeability decreases. Reduction of gradeability

Table 5. Results of first method

DOH	PEM [kW]	PICE [kW]	Number of Battery Modules	Mass [kg]	Fuel Economy [m/g]	0-60 mph Accelera-tion Time [s]	40-60 mph Acceler-ation Time [s]	0-85 mph Accelera-tion Time [s]	Maximum Speed [mph]	Gradeability [%]	Emissions [g/mi.]			Distance In 5 s [ft]
											HC	CO	NO_x	
0.35	33	61	27	1738	74.8	10.3	5	20.1	126.7	18.1	0.215	0.957	0.181	160.6
0.4	38	56	27	1734	77.1	10.7	5.3	21.2	126.7	17.1	0.199	0.877	0.173	159.4
0.45	42	52	27	1728	79.2	11.2	5.6	22.5	126.8	16.1	0.183	0.796	0.166	157.1
0.5	47	47	27	1724	81.3	11.6	5.9	23.6	126.9	15.2	0.172	0.752	0.162	155.4
0.55	52	42	27	1720	83.4	12.3	6.3	25.3	123.6	14.1	0.156	0.675	0.153	152.8
0.6	56	38	27	1715	85.1	12.9	6.7	26.8	120.8	13.3	0.143	0.612	0.145	150.7
0.65	61	33	27	1710	87.9	13.7	7.2	29.1	117	12.2	0.128	0.547	0.135	147.8

Table 6. Results of second method

DOH	PEM [kW]	PICE [kW]	Number of Battery Modules	Mass [kg]	Fuel Economy [m/g]	0-60 mph Accelera-tion Time [s]	40-60 mph Acceler-ation Time [s]	0-85 mph Accelera-tion Time [s]	Maximum Speed [mph]	Gradeability [%]	Emissions [g/mi.]			Distance In 5 s [ft]
											HC	CO	NO_x	
0.5	47	47	28	1735	81.2	11.5	5.8	23.4	126.9	15.4	0.172	0.751	0.162	156.5
0.55	52	42	31	1764	82.9	11.9	6	24.2	126.2	14.8	0.156	0.674	0.154	154
0.6	56	38	33	1759	84.5	12.1	6.2	24.9	124.9	14.3	0.143	0.61	0.145	154.2
0.65	61	33	36	1809	88.1	12.4	6.4	25.7	123.5	13.8	0.127	0.54	0.135	153.8

for first and second methodology is noticeable, but if the proposed methodology is used, reduction of gradeability seems to be gradual.

Figure 16 shows the distance that vehicle covers in 5 seconds of its journey. This parameter is one of the PNGV criteria that is satisfied while applying proposed methodology (third method). As seen from Fig. 16, if the proposed methodology is applied, the car covers much more distance in 5 seconds, in comparison with other two methodologies. It is also observed that by applying the proposed methodology, the distance covered in 5 seconds of car is always higher than 159 ft.

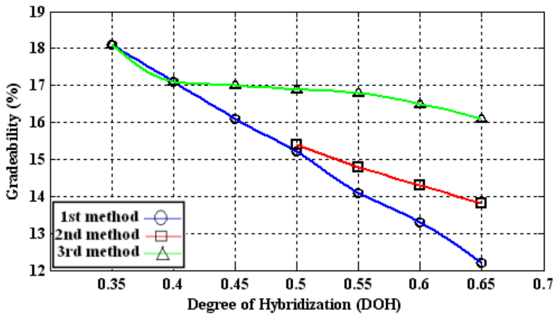

Fig. 15. Gradeability vs. DOH

Table 7. Results of third (proposed) method

DOH	PEM [kW]	PICE [kW]	Number of Battery Modules	Mass [kg]	Fuel Economy [m/g]	0-60 mph Acceleration Time [s]	40-60 mph Acceleration Time [s]	0-85 mph Acceleration Time [s]	Maximum Speed [mph]	Gradeability [%]	Emissions [g/mi.]			Distance In 5 s [ft]
											HC	CO	NO_x	
0.35	33	61	27	1738	74.8	10.3	5	20.1	126.7	18.1	0.215	0.957	0.181	160.6
0.4	38	56	27	1734	77.1	10.7	5.3	21.2	126.7	17.1	0.199	0.877	0.173	159.4
0.45	42	52	33	1794	79.2	10.7	5.3	21.3	126.8	17	0.183	0.797	0.167	159.9
0.5	47	47	38	1845	80.9	10.7	5.3	21.3	126.8	16.9	0.171	0.738	0.161	159.7
0.55	52	42	44	1907	83.1	10.8	5.3	21.4	126.8	16.8	0.154	0.661	0.152	159.9

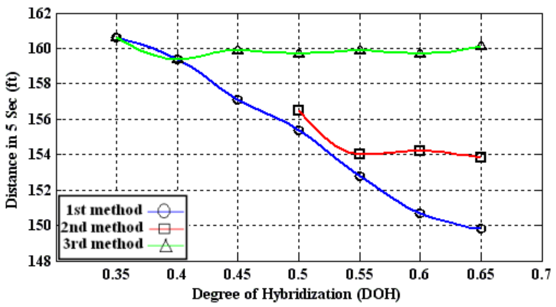

Fig. 16. Distance covered in 5 seconds vs. DOH

7 CONCLUSION

In this paper, an efficient methodology has been proposed for deciding about the number of battery modules, in the hybrid electric vehicles. The proposed methodology, makes it possible to choose higher values for DOH in hybrid cars to have higher levels of fuel economy and lower emissions. It also guarantees high performance of the car. On the other hand, heaviness and hugeness of the car imposed by the proposed methodology are of its disadvantages. If it be possible to produce and manufacture batteries with higher power density and lower volume (it won't take long time, considering the fast advancement in battery manufacturing technology), the proposed methodology will be quite practical.

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