Performance Analysis of Hybrid Electric Vehicle over Different Driving Cycles

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Abstract. Article aims to find the nature and response of a hybrid vehicle on various standard driving cycles. Road profile parameters play an important role in determining the fuel efficiency. Typical parameters of road profile can be reduced to a useful smaller set using principal component analysis and independent component analysis. Resultant data set obtained after size reduction may result in more appropriate and important parameter cluster. With reduced parameter set fuel economies over various driving cycles, are ranked using TOPSIS and VIKOR multi-criteria decision making methods. The ranking trend is then compared with the fuel economies achieved after driving the vehicle over respective roads. Control strategy responsible for power split is optimized using genetic algorithm. 1RC battery model and modified SOC estimation method are considered for the simulation and improved results compared with the default are obtained.

1. Introduction

Hybrid electric vehicle (HEV) has turned up as a promising solution for the automotive industries in terms of reduced toxic emissions. As two power sources, battery and engine are present, an intelligent power split energy management strategy should be implemented to split the power to achieve better fuel economy. HEV's performance will obviously vary over the type and conditions of road, driver's aggressiveness/behavior and weather conditions. Kuhlar and Karstens [1] and Fomunung [2] introduced few parameters which characterize the roads. These parameters have been used to model emissions or fuel economies by others. These parameters are able to describe a driving cycle (DC) behavior but can't clearly identify a DC which may result in the best fuel economy (FE). The aim of the study is to find parameters of DCs, which impacts the FE. Using size reduction techniques, few governing parameters are selected and with these parameters DCs are ranked using 'Technique for order preferences by similarity to an ideal solution' (TOPSIS) and 'The Vlse Kriterijum-ska Optimizacija Kompromisno Resenje' (VIKOR). The vehicle is then run over the different considered DCs to find out their FE using genetic algorithm (GA) based control strategy and then ranked accordingly. These two results are compared to get a sense that how the parameters are linked with FE.

In most of the literature ten parameters are generally considered to characterize a DC. These parameters for seven different city DCs are collated in table1. The authors are interested in identifying the dominant parameters. Principle component analysis (PCA) and independent component analysis (ICA) are dimension reducing techniques and retain the important properties of the dataset. PCA developed by Karl [3] and Hotelling [4] is a statistical procedure to un-correlate the variable and reduce the dimension of the data. PCA yields orthogonal vectors of high energy content in terms of covariance. ICA also decomposes the variables into smaller sets and extracts the independent variables from a multivariate dataset. ICA was developed by Jueten and Herault [5] and Comon [6] to solve cocktail party problems and for blind source separation. DC data sets are reduced here using ICA and PCA and some of these reduced parameters are maximized and others are minimized to compute FE. This requires multi-criterion decision making (MCDM) measures. Valuable MCDM methods like TOPSIS and VIKOR, are applied here to rank DCs in the order of their FE. Further, to support the analysis obtained by these methods, an intelligent power split control strategy is developed using GA. Engine on/off trend helps in achieving this. To control the engine on/off, threshold values of governing parameters (which are responsible for power split) are obtained using optimization techniques and FE is determined.

2. Feature extraction of driving cycles

Table 1 lists the parameters of DCs. To extract features of these DCs, PCA and ICA methods are used and explained in the subsequent sections.

Table 1. City driving cycle characteristics

Driving cycle / Parameters	UDDS	ECE_ EUDC	LA92	US-06	Indian	Japan 10-15	WVUCITY
Time (s)	1369	1225	1435	600	2689	660	1408
Distance (miles)	7.45	6.79	9.82	8.01	10.87	2.59	3.3
Max. speed (mph)	56.7	74.56	67.2	80.3	38.87	43.48	35.82
Avg. speed (mph)	19.5	19.95	24.61	47.97	14.54	14.09	8.44
Max. acceleration (ft/s^2)	4.84	3.46	0.12	12.32	5.68	2.6	3.75
Max. deceleration (ft/s^2)	-4.84	-4.56	-12.91	-10.12	-6.9	-2.73	-10.62
Avg. acceleration (ft/s^2)	1.66	1.78	2.21	2.2	1.06	1.87	0.97
Avg. deceleration (ft/s^2)	-1.9	-2.59	-2.47	-2.39	-1.29	-2.12	-1.27
Idle time (s)	259	339	234	45	267	215	427
No of stops	17	13	16	5	52	7	14

2.1. Principal Component Analysis

PCA is useful to the dataset which heavily rely on Gaussian features and utilizes first and second moments of measured data. PCA displays principal components (PCs) which are made of the variables. These PCs are unit vectors and are orthogonal identity matrix. Here, principal component 8 (PC8) onward all PCs are found to be zero. PC1, PC2 and PC3 are significant and are considered for interpretation. PC1 is strongly correlated with eight of the 10 original variables. PC1 can be viewed as a measure of distance, avg. speed, max. acceleration, max. deceleration, avg. acceleration, avg. deceleration and number of stops. DCs with better fuel economy would tend to have lesser values of avg. speed, max. acceleration and avg. acceleration whereas higher values of maximum deceleration, avg. deceleration and number of stops. PC2 increases with only one of the values, i.e. decreasing distance. PC3 increases if the idle time in the driving cycle increases and explains the impact of idle time. Identification of the variables of driving cycle through PCA will be useful in ranking a DC and while analyzing its fuel economy.

2.2. Independent Component Analysis

For the hidden feature extraction another popular technique, ICA is also used. ICA is a statistical and computational technique to identify the meaningful hidden features. In contrast to PCA, ICA extracts six parameters which are significant for analysis. These are trip time, average speed, maximum deceleration, average acceleration, idle time during the trip. The smaller data sets received by PCA and ICA do not have same parameters, so selecting one of them is important. Generally, PCA is applicable to Gaussian data and is restricted to the first and second moments of the data, whereas ICA is applicable to non-Gaussian data and explores higher order moments. Thus, it is important to identify the nature of DC data on which these techniques are applied.

3. Nature Identification of driving Cycles

To analyze the nature of DCs, probability distribution functions are determined. The mean and standard deviations (SD) of the distributions are recorded and listed in table 2. It can be observed that no DC follows a normal distribution with mean=0 and SD=1. This enables us to choose ICA for feature extraction as ICA fits for non-Gaussian data set.

Table 2. Mean and standard deviations of various distributions

Driving cycle	Mean (Location parameter)	SD (Scale parameter)	Distribution type
INDIAN	-3.1518	33.790	Generalized Pareto
UDDS	4.2804	5.0278	Gumbel maximum
ECE_EUDC	-1.7264	22.386	Johnson SB
LA92	-1.7373	35.690	Johnson SB
WUVCITY	1.3645	2.4398	Generalized extreme value
US06	-5.1976	80.503	Generalized Pareto
JAPAN10-15	-1.7264	22.386	Johnson SB

4. Ranking method implications

VIKOR and TOPSIS methods are applied to rank the DCs for FE prediction. VIKOR is multi-criteria optimization and a compromise solution method developed by Opricovic and Tzeng [7] and TOPSIS is a multi-attribute decision making method and introduced by Yoon and Hwang [8]. VIKOR and TOPSIS are applied to the extracted features from ICA to rank various DCs in order to get estimation about their FEs without running a vehicle (without simulation). The results for VIKOR and TOPSIS with ICA are tabulated in table 3. The results infer that Indian DC is getting invariably first position with all the ranking methods. Hence, Indian road conditions are proven to be better for HEVs as they will consume lesser fuel and minimum emissions. The low acceleration rate, lower speed and frequent start/stops prompt the motor to work more and keep the engine in shutting off condition or operate in its most efficient region. This becomes a favorable condition for an efficient HEV. Though, other DCs are not found to be of the same rank and a close observation of LA92, UDDS, WVUCITY and ECE_EUDC reveals that most of their parameters are very close to each other, hence taking VIKOR/TOPSIS towards the unintended ranking level.

Table 3. Driving cycle ranking by VIKOR and TOPSIS

VIKOR with PCA	VIKOR with ICA	TOPSIS with PCA	TOPSIS with ICA	FE ranking
Indian	Indian	Indian	Indian	Indian
WVUCITY	LA92	WVUCITY	LA92	UDDS
JAPAN 10-15	UDDS	JAPAN 10-15	WVUCITY	ECE_EUDC
UDDS	WVUCITY	UDDS	UDDS	LA92
LA92	ECE_EUDC	ECE_EUDC	ECE_EUDC	WVUCITY
ECE_EUDC	US06	LA92	US06	US06
US06	JAPAN 10-15	US06	JAPAN 10-15	JAPAN 10-15

5. Analysis of fuel economy over different driving cycles

The FE of Prius over considered DCs is measured using GA in ADVISOR. GA is a robust and feasible approach and solves complex optimization problems. The available battery power is governed by state of charge (SOC). ADVISOR uses Ampere Hour Counting method for SOC estimation. But, the importance of open circuit voltage for SOC estimation is also emphasized in literature. Thus, SOC estimation algorithm is accordingly modified and incorporated in ADVISOR library. In this paper, 1RC (parallel combination of 1 RC components in series with internal resistance) model along with modified SOC estimation method is used to perform the simulations. Threshold values of governing parameters responsible to turn on/off the engine are estimated using GA and corresponding FEs are recorded [9]. Table 4 records the threshold values of these parameters, namely cs_eng_on_soc, cs_min_off_time, cs_min_pwr, cs_electric_launch_spd and cs_eng_min_spd for considered DCs. Table 5 collects the efficiencies of engine, motor and generator and FEs over various DCs with the threshold values obtained in table 4. Among all the DCs, Indian urban DC is found to be best in terms of FE. With a tag of the second most populous country today which will become first in 2022 surpassing China, India, will demand deadly number of vehicles on the road to fulfil the requirement. On an average 11-12% per year increase in number of motorized vehicles on Indian roads is observed. India's CO_2 emission continues to increase by 7.8 percent in 2014. India emitted 170 million tons of CO_2 in 2014 and became the largest contributor to global emission growth. India became fourth largest CO_2 emitting country in 2014 while it was fifth in 2011. So, an alternative approach in terms of HEV should be opted to fulfil its growing population demand while reducing the CO_2 emissions. The favorable road conditions paves pathway to invite hybrid vehicles on Indian roads for greener tomorrow.

Table 4. Optimized parameter values of drive cycles using GA

Drive cycle	SOC(%)	Off time(s)	Power(watt)	Electric speed(rad/s)	Enginespeed(rad/s)
UDDS	39.65	9.61	9276.9	10.79	209.43
ECE_EUDC	33.08	6.10	6805.9	12.48	281.66
LA92	38.91	4.26	9306.6	11.08	254.23
US06	38.01	9.80	9318.6	10.63	254.92
Indian	33.60	6.70	9280.2	10.88	252.97
Japan 10-15	33.10	9.71	9762.3	10.64	230.53
WVUCITY	39.11	2.13	9128.3	10.07	230.12

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Table 5. Efficiency evaluation of system components using GA

Drive cycle	Engine efficiency(%)	Motor efficiency(%)	Generator efficiency (%)	FE(mpgge)
UDDS	30.30	83.65	64.77	59.32
ECE_EUDC	27.32	81.67	92.46	52.25
LA92	31.48	82.59	67.22	48.18
US06	33.08	82.54	60.58	44.72
Indian	30.34	84.17	23.56	61.44
Japan 10-15	19.16	92.89	80.54	43.01
WVUCITY	21.07	79.39	74.63	46.99

Table 6 performs the comparison between default SOC estimation method with R_{int} battery model and modified SOC estimation method with 1RC battery model. Modified SOC estimation algorithm in table 6 is either improving FE or speed traces or both. In general cases, idling is allowed at the stops. But if, idle stopping is implemented, the significant amount of fuel can be saved. The comparative study of the FEs in case of idle stopping with zero engine speed and engine on is tabulated here. Table 7 shows noteworthy improvement in FEs for all DCs but Indian DC is dominating. Two major reasons idle time and number of stops may play momentous functionality. Idle time is considerable, but a greater no. of stops will recuperate more kinetic energy which will motivate the vehicle to run more on electrical energy, hence improves FE. Further, lower acceleration rate and lower speed of Indian DC make it in favor of HEVs. Indian DC also provides highest regenerative efficiency.

Table 6. Fuel economy comparison with default and modified SOC estimation method

Drive cycle	Fuel economy with default SOC estimation method and R_{int} model	Fuel economy with modified SOC estimation method and 1RC model
UDDS	59 (with trace miss)	59.3291 (without trace miss)
ECE_EUDC	46.7 (without trace miss)	52.2579 (without trace miss)
LA92	44.3 (with trace miss)	48.1884 (without trace miss)
US06	42 (with trace miss)	44.7263 (without trace miss)
Indian	54.7 (with trace miss)	61.4473 (without trace miss)
Japan 10-15	41 (without trace miss)	43.00 (without trace miss)
WVUCITY	46.7 (with trace miss)	46.9988 (without trace miss)

Table 7. Fuel economy comparison with and without engine idling

Drive cycle	FE without EI (mpgge)	FE with EI (mpgge)	FE improve-ment (%)	Idling time (%)	No. of stops	Regenerative efficiency
UDDS	59.32	62.33	5.06	18.91	17	119.591
ECE_EUDC	52.25	54.05	3.44	27.67	13	-78.707
LA92	48.18	50.44	4.69	16.30	16	185.333
US06	44.72	51.58	15.3	7.500	5	217.773
Indian	61.44	85.32	38.8	9.929	52	250.308
Japan 10-15	43.00	44.45	3.37	32.57	7	-381.935
WVUCITY	46.99	48.74	4.61	30.32	14	-193.287

6. Validation of control strategy

The suitability of the proposed control strategy is calculated through numerous simulations performed over different DCs repeated over diverse geographic provinces. The simulations are performed on 1RC battery model with the modified SOC estimation method. At all instances, the demanded power and speeds are met and can be observed in figure 1. Various studies also show that HEVs can give better FE on Indian city roads in comparison to the developed country road [10].

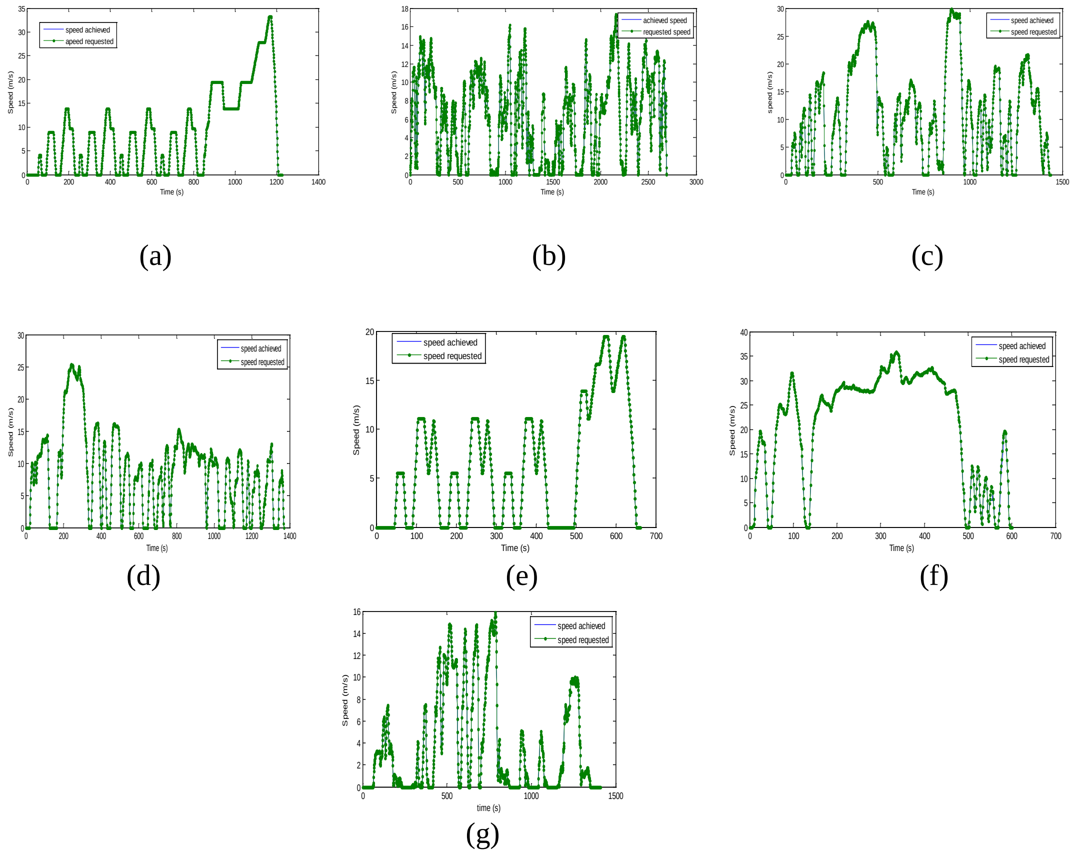

Figure 1. Speed and time traces of driving cycles (a) ECE_EUDC, (b) INDIAN, (c) LA92, (d) UDDS, (e) US06, (f) JAPAN 10-15, (g) WVUCITY

7. Conclusion

The efficiency of an HEV obviously depends on the road profiles. A profile is a composition of various parameters. In this paper, few vital parameters are identified using size reduction techniques and based on these DC are ranked in order of their fuel economy using multi criterion optimization methods. The results are further validated using GA based intelligent power split control strategy. It is concluded that the Indian urban DC is promising and provides higher fuel efficiency for an HEV as compared to other countries. The favorable Indian road profile will attract more people to use HEVs, thus boom in the automobile manufacturing market is expected. This will further reduce toxic emissions and will contribute to the Indian economy. It is also recommended that ICA should be applied rather than PCA for extracting DC parameters to analyze the performance as they follow non-Gaussian distribution. Engine idling should be considered as a powerful feature for improving fuel economy on city roads.

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