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Performance Analysis Of Ev Hev And Fcv With Respect To Electric Motor Mass Reduction

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Abstract: Plug in electric and fuel cell vehicles are said to be the next generation vehicles whereas hybrid electric vehicles have already established its roots in the market. The end consumers need better fuel efficiency, drive range, cost effective without any compromise in comfort and luxury and the government bodies require independency on foreign oil, better carbon footprint and sustainability in transportation. It has also been observed that the weight of vehicles is increasing from one generation to the next generation. Heavier the vehicle more will be the fuel consumption and emission. The mass reduction of drive train components has become necessary to provide space for performance improvement of the vehicles. The advancement in the area of material technology, casting technology and use of lightweight materials has paved the way for the motor mass reduction. With the help of simulation on NREL ADVISOR small car with three dive train technology EV, HEV and FCV and conventional vehicle on three drive cycle HWFET, US06 and UDSS , this paper investigates how the performance of HEV, FCV and EV get affected and by the motor mass reduction of these vehicle while keeping other vehicle parameters unchanged.

***Index Terms* -** Electric vehicle, Fuel cell vehicle, environment, emission control, vehicle performance, motor mass.

I. INTRODUCTION

The need of environmental and social sustainability puts tremendous pressure on the policy makers to make stringent policies for the transportation sector (Waide P et. al., 2011, Lynette C et. al. 2007). This is why this sector is generating various areas for research. These days the automobiles are incorporating more electronics and power electronics devices on board. The devices like air conditioning, heater, audio system etc. are no more considered as luxury but important for the vehicle to be sell out in the market. To accommodate various end consumers requirements, safety performance, driver assistance systems, airbags, requirement of reinforced body structure etc, the size and weight of cars are increasing with every new model. The 2004 model Toyota Prius that is the second generation Prius has length measured as 4450 mm and weighed 1325 kg whereas its predecessor had length 4308mm and weight 1254 kg. Similarly the first generation Honda Insight Hybrid electric vehicle had length 3945 mm and weight 891 kg and its successor the second has length 4376mm and weight 1237 kg.

Under normal driving condition on flat road and on grade the tractive power generated by of a vehicle drive line is given as (Ehsani M et. al. 2005)

$$P_t = \frac{V}{1000\eta_t}\left(M_v g f_r + \frac{1}{2}\rho_a C_D A_f V^2 + M_v g i\right) \text{ kw} \quad (1)$$

M_v is vehicle mass in kg, f_r is rolling resistance co-efficient, air density ρ_a, front area A_f in m^2, aerodynamic drag coefficient C_D is a constant, r is the wheel radius in m, η_t is the transition efficiency, V is the vehicle speed in m/sec, i is the grade and g is the acceleration due to gravity.

In equation (1) the first term $M_v g f_r$ is the resistive friction force between tire and road known as rolling resistance on the vehicle. This resistance is directly proportional to the vehicle weight so more drive line power will be lost to overcome rolling loss. Second term in equation (1) is the resistance due to aerodynamic drag. Aerodynamic drag does not depend on the vehicle mass but directly proportional to the frontal area of the vehicle and square of the vehicle speed. Aerodynamic drag resistance is reduced by optimum streamline design with headlamp and all wheels covered in the body. If the sizes of the vehicle increases then this drag resistance increase and again at high vehicle speed, large percentage of tractive effort will be required to overcome the aerodynamic drag resistance. One more resistance that is required to be balanced by drive train power of the vehicle is the grade resistance. Grade resistance is also directly proportional to the weight of the vehicle that is $M_v g$. The gradeability of vehicle reduces with increasing mass of the vehicle.

Performance of a vehicle is measured by the maximum speed, maximum acceleration and gradeability at certain speed. Increasing the engine power or electric motor power rating can obviously enhance the vehicle performance to a large but this option will increase the flue gas emission, increase the space taken by vehicle drive line and reduce the space for passenger utilities and luxuries. Also the weight of the vehicle will increase. In that case vehicle may pass certain performance criteria but increased weight of the vehicle may put a limitation on its performance. So increasing the size of drive train components of a vehicle is not a good option to achieve performance of the vehicle.

Light weight car design is an area where continuous research is going on worldwide. Use of aluminum and its alloys is established in many parts of vehicle such as car body, doors, front structures, radiators, etc. . Many auto industries in Europe are working toward the use of aluminums even in the heaviest part of car that is Body in White (BIW) which shares around 30% of total vehicle weight and which is conventionally a steel structure. Reduction of vehicle mass is also done by the use of plastic in roof area, bumper etc. For improved performance of vehicle, the drive train components have to be resized and generally the size of the drive train increases. Next generation vehicles electric, fuel cell or plug in electric vehicles have simple power train architecture comprise of many electronics and power electronic devices. These power electronics and electronics devices are compact and light weight compared to various drive train components used in conventional gasoline fueled vehicles. The major drive components adding mass to the overall mass of the vehicle are energy storage system (battery), traction motor, generator and internal combustion engine (ICE) in hybrid electric vehicle. Without increasing the size of drive train components, the performance these vehicles can be increased by reducing the mass of battery and traction motor. By the use of light weight metals like aluminum and magnesium and optimizing the core design, winding design, use of manmade light weight magnetic materials, making light weight motors especially for electrification of vehicles has already accepted as a challenge by electric motor manufacturers (S. Pagerit S et. al., 2006, Farrington et. al., 2000, Hofer J et. al., 2014.)

Vehicle simulation software are developed for drive train analysis, performance evaluation, bench marking, new drive train design, components sizing, energy optimization, efficiency calculation etc. Using National Renewable Energy Laboratory (NREL) Advance Vehicle Simulator (ADVISOR), this paper is focused on effect of traction motor mass reduction on the performance of fuel cell vehicle, electric vehicle and hybrid electric vehicle on three drive cycles HWFET, US06, UDDS.

II. RELATION BETWEEN VEHICLE PERFORMANCE AND TRACTION MOTOR MASS

Performance of a vehicle is commonly judged by the maximum cruising speed on flat road with full power of engine or motor. Maximum speed related to maximum tractive effort and maximum tractive effort is based on the maximum torque developed by the vehicular power plant.

For an induction motor

$$Torque = \frac{Mechanical\ power\ output}{angular\ velocity\ of\ the\ rotor} \quad (2)$$

Mechanical power output = Electrical power developed in the stator - loss (3)

The electrical power developed in the stator is related to the motor dimension as

$$Q = C(D^2L)N \quad (4)$$

Where D is the inner diameter of the stator, L is the length of the motor, N is the speed in RPM and C is the output coefficient.

$$C = 17.4 \times 10^{-5} B\ ac\ Cos\emptyset\ \eta \quad (5)$$

Where B is the average value of fundamental flux density, ac is the Ampere Conductor and is known as Electric loading and is a factor of D, η is the efficiency of motor.

From equation (4), if we increase the motor internal volume electrical power developed will increase. By rearranging the equation (4) for the speed

$$D^2L = Q/CN \quad (6)$$

Internal volume of the motor should decrease to increase the speed. Torque developed by the motor is determined by

$$T = P_{mech}/\omega_m \quad (7)$$

ωm is the rotor angular velocity Pmech is the electrical power minus the winding losses. Torque and speed of induction motor are inversely proportional to each other. Bigger size motor will develop higher torque, but the maximum speed achieved in that case will be less.

From the above discussion power density is the more important criteria for traction motor selection. Mass of induction motor can be reduced without disturbing the power density. The size of motor can also be altered by changing D and L without affecting torque or speed of the motor.

III. DRIVE CYCLE TEST OF VEHICLES FOR PERFORMANCE EVALUATION WITH MOTOR MASS REDUCTION

Three drive cycle tests are performed on three types of drive train configuration of a small car. The test drive cycles are HWFET, UDDS and US06 drive cycle. HWFET is the Highway Fuel Economy Test where vehicle is allowed to run for 12-13 minute with average speed requirement of 77.58 km/h and 96.4 km/h maximum speed. The Urban Dynamometer Driving schedule (UDDS) represents city driving condition with low average speed of 31.51 with 17 stops in almost 12 km distance to be travelled in 22-23 minute. Vehicle acceleration performance can be judged very well in this type of driving schedule. This driving schedule is also important to measure different mechanical and electrical losses in other drive train components also like bearing losses, loss in energy storage system (ESS) due to frequent charging and discharging, wheel loss etc. .US06 drive cycle is basically used to measure vehicular tailpipe emission but as it includes high speed cruising with average speed of 77.2 km/h but high maximum speed requirement of 129.23 km/h and maximum acceleration demand of 3.76 m/s2 make it interesting for the performance test of a vehicle in which the tractive power is generated by an electrical induction motor.

The performance of Electric Vehicle (EV), Fuel Cell vehicle (FCV) and Hybrid electric Vehicle (HEV) that are included in these drive cycle tests are small passenger cars with vehicle total mass 1450 kg including drive train components mass with and cargo mass of 136 kg. at the beginning with traction motor (induction motor) maximum power of 75 KW. Parallel power train topology has been used to test HEV performance as Series HEV perform very similar manner as the performance of EV.

IV. FUEL ECONOMY IMPROVEMENT WITH MOTOR MASS REDUCTION

The weight of traction motor used to be 10-12% of vehicle total weight reduction in fuel consumption is not very pronounced for the small vehicle. Result for heavy vehicles will be more pronounced i.e. considerable reduction in fuel consumption is possible in case of heavy vehicles. The HWFET, UDDS, US06 cycle tests for fuel economy verification with variation in motor mass is shown in Fig1for EV, FCV, and HEV. Neither EV nor FCV consume fossil fuel so their equivalent gasoline consumption record has been considered for the study. The decrement in fuel consumption is quite pronounced at 50% of the motor mass. Small change in motor mass in vehicles may not affect its fuel consumption trend considerably. The three drive cycle average rate of reduction in fuel consumption are found to be 0.0419, 0.0227 and 0.0247 for HEV, FCV and EV respectively. The trend of the lines in these graphs indicates that the relation between fuel consumption and motor mass reduction is not exactly linear. While HEV gives the best performance with highest rate of reduction of 0.0734 in US06 drive cycle, FCV shows very different trend where fuel consumption starts increasing when the motor mass is reduced by large amount. EV has slow and steady performance due to its own characteristics.

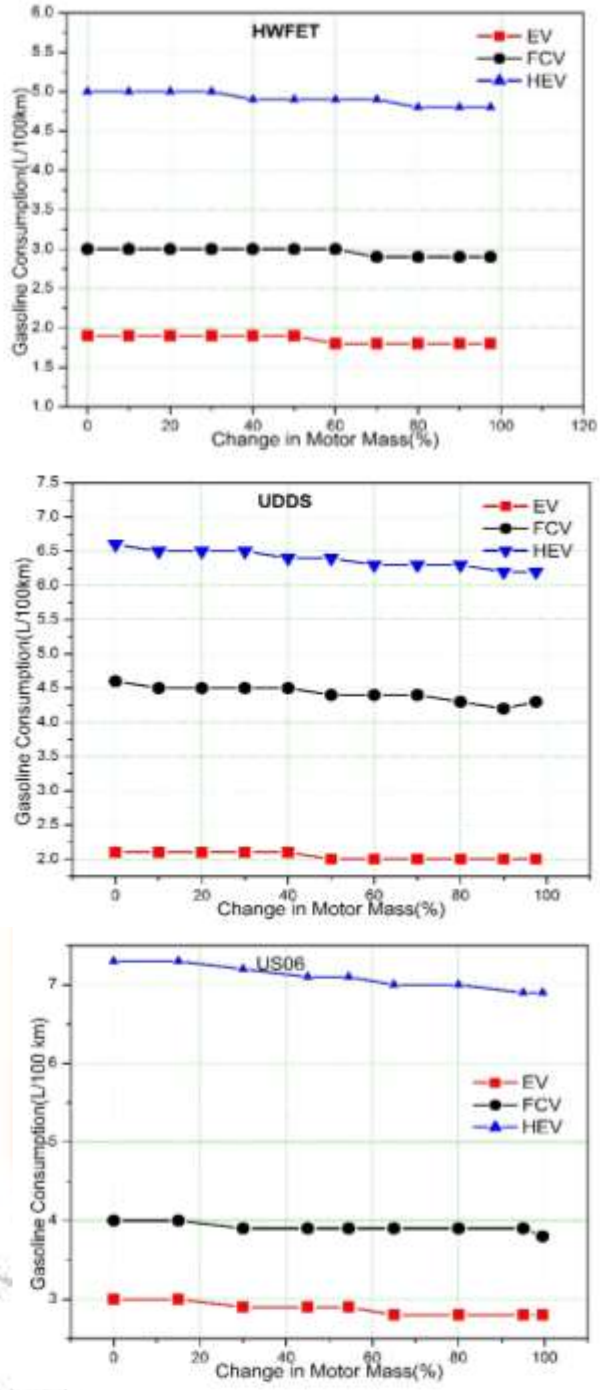

Fig.1 Variation in fuel consumption with motor mass reduction

V. ACCELERATION PERFORMANCE WITH MOTOR MASS REDUCTION

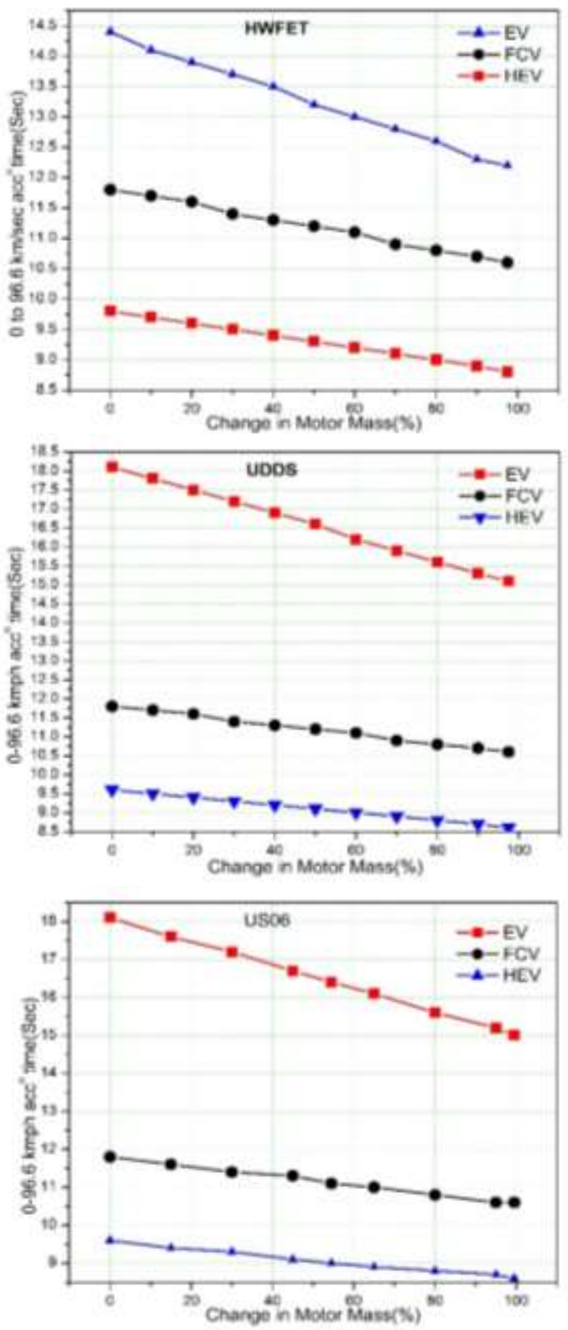

Fig.2 Variation in time taken to accelerate from 0-96.6,kmph with motor mass

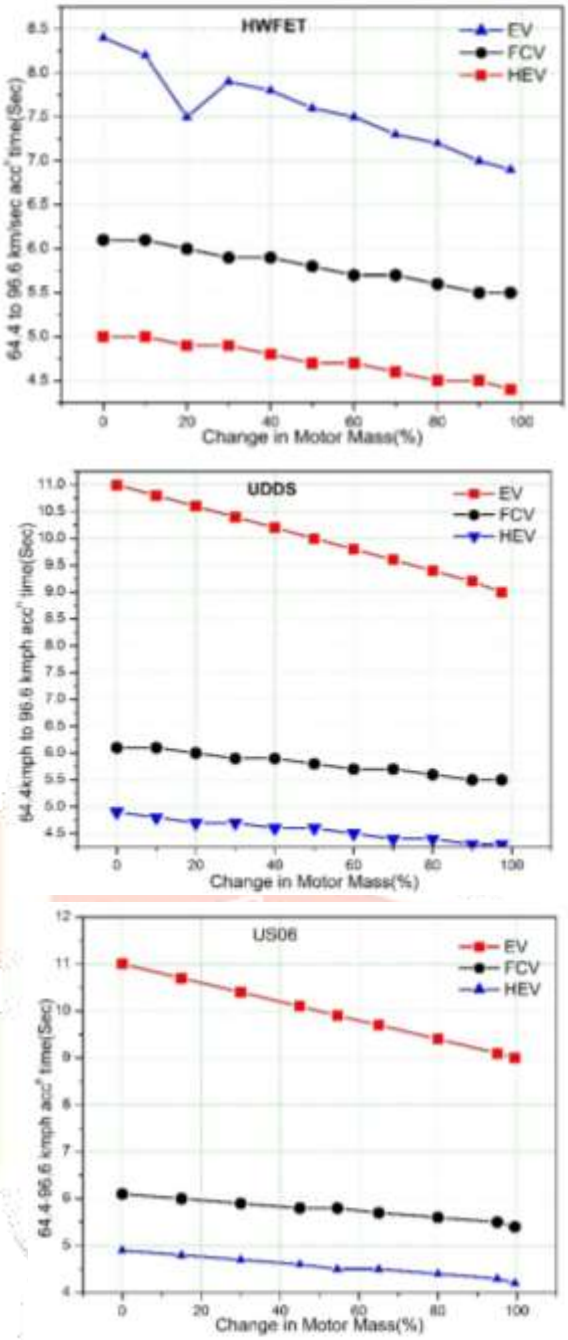

Fig.3. Variation in time taken to accelerate from 64.4 to 96.6 kmph with motor mass

III.

Acceleration performance of a vehicle depends on factors like road pattern, driver's nature of d

Table 1

Percentage Improvement in acceleration time required after 50% reduction in Motor mass

Desired speed(kmph)	Drive cycle	EV	FCV	Parallel HEV
0-96.6	US06	9.4	5.9	6.25
	UDDS	8.3	5.08	5.2
	HWFET	8.33	5.08	5.10
64.4-96.6	US06	10	4.9	8.16
	UDDS	9.1	4.9	6.1
	HWFET	9.5	4.9	6
0-137	US06	--	5.9	6.6
	UDDS	--	5.1	6.09
	HWFET	9.5	4.9	6

riving, cargo mass and maximum torque of traction motor. Acceleration performance also depends on the vehicle initial speed and the required final speed. Maximum acceleration depends on the motor maximum power and so it remains constant. Here the vehicle maximum acceleration is constant at 5 km/sec2 for all drive train topology and in all three drive cycles. But with the reduction in motor mass the losses in motor as well as losses in different drive train components are getting reduced. Another reason for loss reduction and vehicle better performance at high speed is the reduced torque requirement at high speed. The graphs shown in Fig 2 shows the relation between the times required to achieve 96.6 kmph speed in HWFET, UDDS, and US06 drive cycles by HEV, EV, and FCV. The three drive trains show improved accelerating capacity but the EV performs better than HEV and FCV in HWFET drive cycle with the slope of the line 0.2414. Fig.3 shows the vehicle propulsion capacity improvement with motor mass reduction from initial speed of 64.4 kmph to 96.6 kmph. The HEV gives fastest improvement in acceleration performance with respect to motor mass reduction in all the three drive cycles. EV shows improvement in nonzero initial speed to high speed acceleration with motor mass reduction. The performance level FCV lies in between that of EV and HEV. Both HEV and FCV have on board fuel converter but the efficiency of FCV fuel converter is much higher than the IC engine which works as fuel converter in HEV. But the weight of FCV fuel converter is also much more than that of IC engine. FCV has advantage of low battery loss and on board battery charging facility so it performs better than the FCV. Table1. Shows the percentage improvement in the time required to accelerate the vehicle from an initial speed of 0 and 64.4kmph after 50% reduction in motor mass. EV is the best performer in this test. EV is not able to achieve very high speed of 137kmph in UDDS and US06 cycle but HWFET cycle which is a smooth and steady drive EV is achieving 137 kmph speed and 12.24% performance improvement with 50% motor mass reduction is very significant. The improvement in vehicle acceleration performance with 50% reduction in motor mass is 6.7% and average improvement in EV, FCV and HEV are observed as 7.43%, 5.21% and 6.2% respectively.

VI. SPEED PERFORMANCE WITH MOTOR MASS REDUCTION

Speed performance of the vehicle is measured by two tests: by calculating the distance travelled by the vehicles in 5 sec and by calculating time taken to travel 0.4 km distance. Fig.4, are the graphs between the distances travelled by the EV. FCV and HEV in 5 sec with motor mass reduction in UDDS, US06 and HWFET drive cycles. The slops of the lines are tabulated in Table2

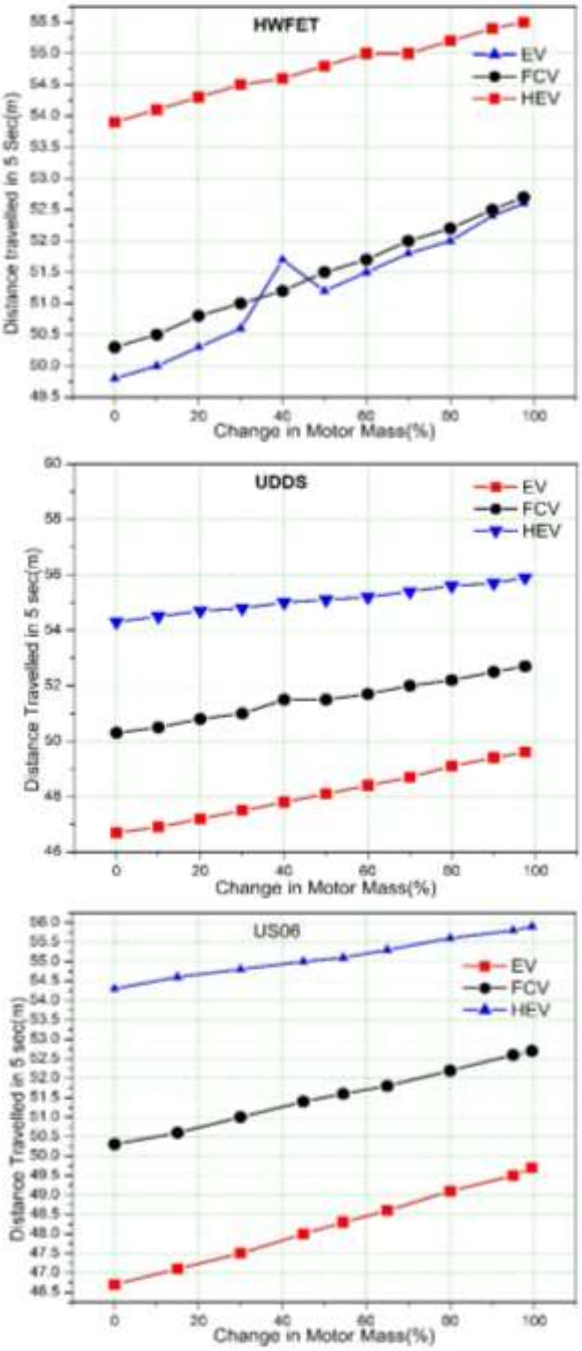

Fig. 4. Variation in distance travelled in 5 sec with motor mass

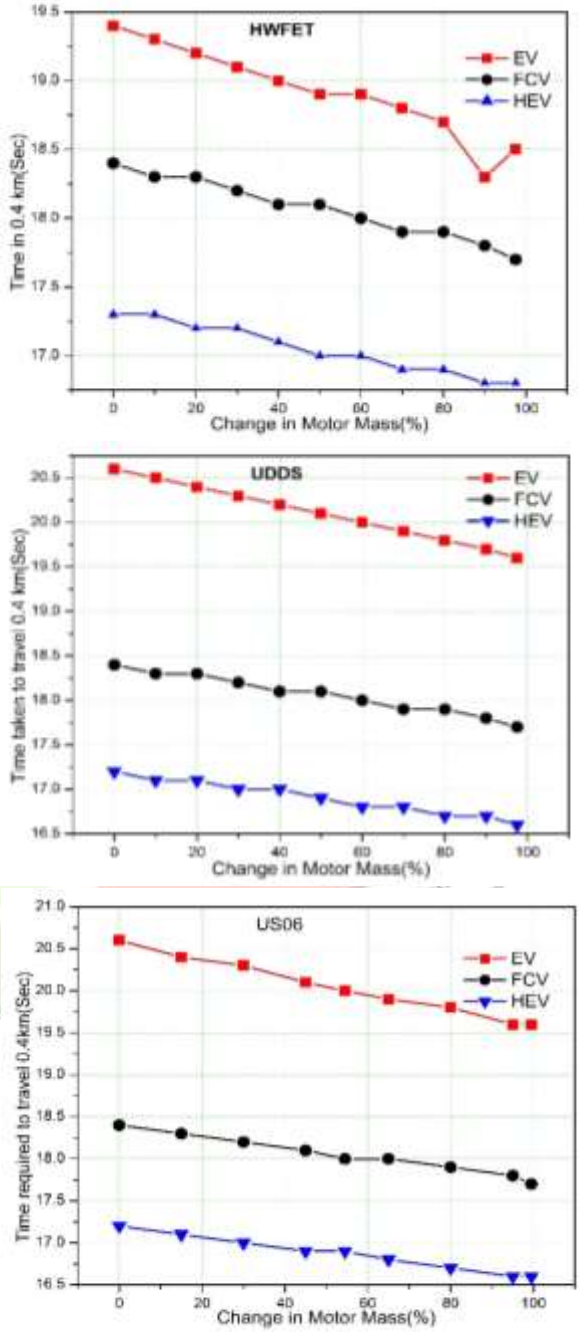

Fig.5. Variation in time taken to travel 0.4 km with motor mass

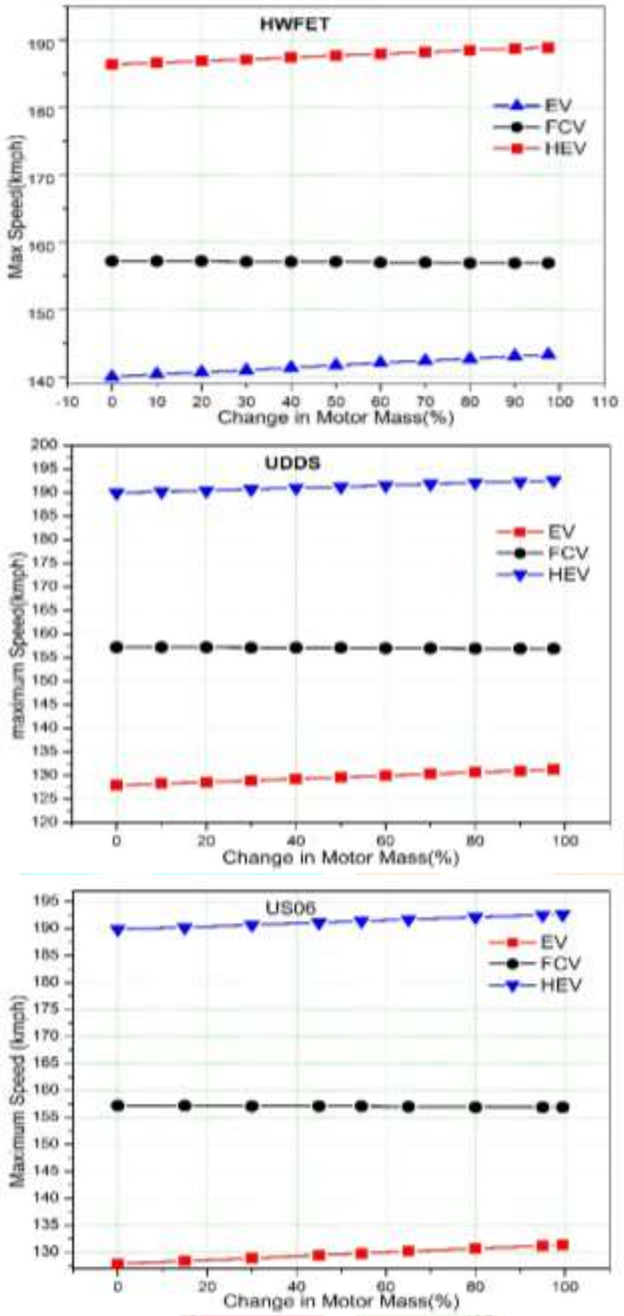

Fig.6. Changes in maximum speed of the vehicles with changing motor mass

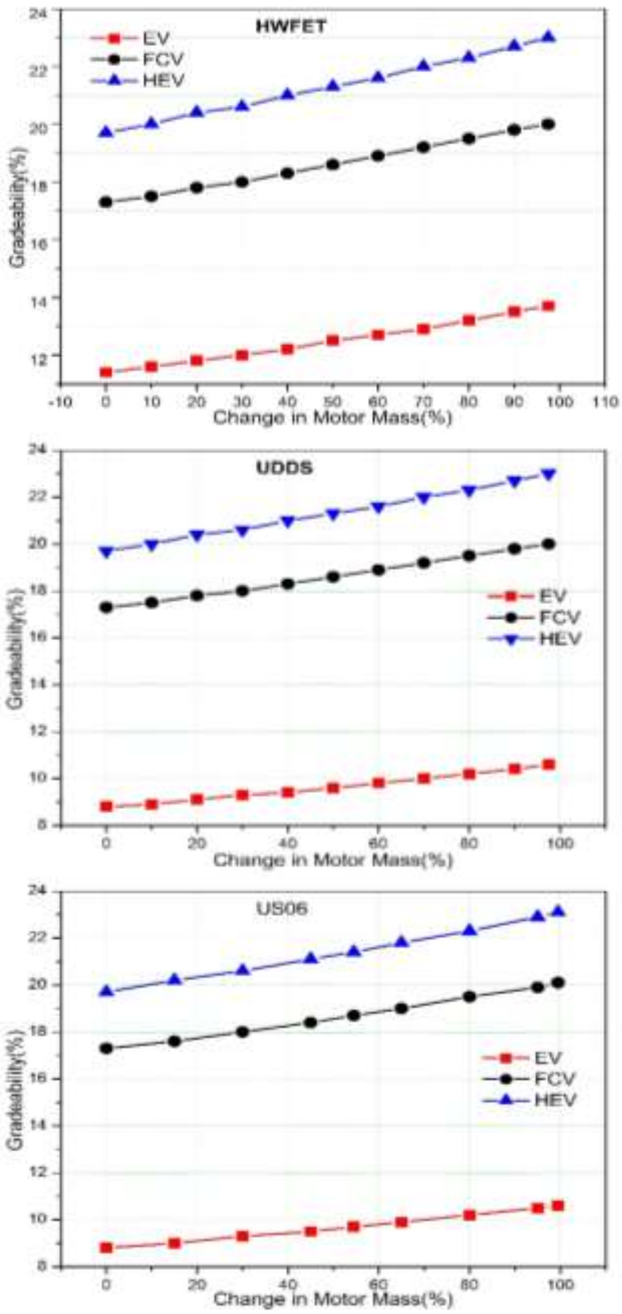

Fig. 7. Effect of motor mass on the gradeability of the vehicles

Table 2
Rate of speed improvement with change in motor mass

Desired performance	Drive cycle	EV	FCV	Parallel HEV
Time to travel 0.4 km	US06	0.126	0.1023	0.1077
	UDDS	0.0955	0.0809	0.079
	HWFET	0.1091	0.0825	0.0763
Distance in 5 sec	US06	0.0767	0.0613	0.0397
	UDDS	0.0585	0.046	0.0297
	HWFET	0.076	0.0485	0.0315
Max speed	US06	0.5669	-0.0433	0.3517
	UDDS	0.3311	-0.0322	0.2566
	HWFET	0.3345	-0.0355	0.2582
Gradeability	US06	0.2317	0.3617	0.43
	UDDS	0.1773	0.272	0.3227
	HWFET	0.2327	0.28	0.3309

From table 2 it is very clear that EV performance is improving with greater slop as compared to HEV and FCV. The increase in distance travelled by vehicles with 50% reduction in motor mass is tabulated in Table 3. EV is the best performer by 3.04% average improvement in distance travelled in 5 sec whereas the average improvement shown by FCV and HEV are 2.45% and 1.54% respectively. This implies that significant increase in speed is possible by using lightweight motor in EV, FCV and HEV. The test result of the time required to travel 0.4 km with respect to the motor mass reduction in different drive cycle is shown in Fig.5. The slop of the lines in the graphs has been tabulated in Table 2.

Table 3
Percentage improvement of speed performance by 50% reduction in motor mass

Desired performance	Drive cycle	EV	FCV	Parallel HEV
Time to travel 0.4 km	US06	2.9126	2.1739	1.7441
	UDDS	2.4875	1.6574	1.7751
	HWFET	2.5773	1.6304	1.7341
Distance in 5 sec	US06	3.4261	2.5844	1.4732
	UDDS	2.9978	2.3856	1.4732
	HWFET	2.8112	2.3856	1.6697
Greadeability	US06	10.2272	8.0924	8.6294
	UDDS	9.0909	7.5144	8.1218
	HWFET	9.6491	7.5144	8.1218

In this test also EV is benefitted most by the motor mass reduction three cycle average slop of 0.1102 but HEV and FCV are closely lagging it with slop of 0.0876 and 0.0885 respectively. Percentage saving in time by 50% motor mass reduction is tabulated in Table 3.Almost 3% improvement in speed can be achieved by 50% reduction in motor mass of the EV. Parallel HEV considered for test has consistency in speed improvement but the behavior of FCV is not consistent in all three drive cycles. As far as the improvement in maximum speed, the trends of the increment are having slops tabulated in table 2.
The maximum speeds of these vehicles are already in the range of 140-190 kmph. The speeds are very high and passenger cars are not expected to run at this speed in normal city drive or highway drive. Still slight improvement can be observed in EV and HEV with more than 50% reduction in motor mass. But FCV has a negative slop and maximum speed decreases with reduced motor mass in this case. The rate of maximum speed reduction is too slow in case of FCV but the performance is contradictory. With this exception one can very well conclude that the speed performance of vehicles improves with motor mass reduction.

VII. GRADEABILITY PERFORMANCE WITH MOTOR MASS REDUCTION

Gradeability obtained in the three drive cycle test for the three vehicular drive train at 88.5 kmph speed with motor mass reduction is shown in Fig.7. The gradeability performance of EV is very poor as compared to that of FCV and parallel HEV. Table 2 shows rate of improvement in gradeability with respect to motor mass reduction.
The pace at which the gradeability is increasing is the least in the case of EV. The gradeability performance FCV is not very far from that of parallel HEV. Table.3 shows that with 50% reduction in motor mass there is around 10% improvement possible in the gradeability of EV with 8.29 % improvement in HEV and 7.7% average improvement in FCV.

VIII. EFFECT OF MOTOR MASS REDUCTION ON TAILPIPE EMISSION

EV, FCV and PEV are considered as the vehicle of future. These vehicles are zero emission vehicles. However HEV can be considered as transition vehicle. Series HEV performs very close to EV, so the effect of motor mass reduction is not important. In series HEV, IC engine is only charging the battery and producing the tractive force. But in parallel HEV which is considered in this test IC engine propels the vehicle in co-ordination with the electric motor, so tailpipe emission can be effected by the motor mass reduction. The graphs shown in Fig. 8 are the tailpipe emission of parallel HEV with respect to motor mass reduction. Reduction in flue gas emission with 50% reduction in motor mass is tabulated in Ttable 4Tailpipe emission reduces with motor mass reduction with maximum improvement can be observed in reduction of CO in all three cycles. Reduction in NOx is pronounced in UDDS and HWFET cycle but the trend of the NOx reduction is not clear in US06 drive cycle and overall performance shows that the NOx emission not affected by motor mass reduction in US06 drive cycle test. From the observation one can also conclude that the vehicular emission is a factor of drive pattern.

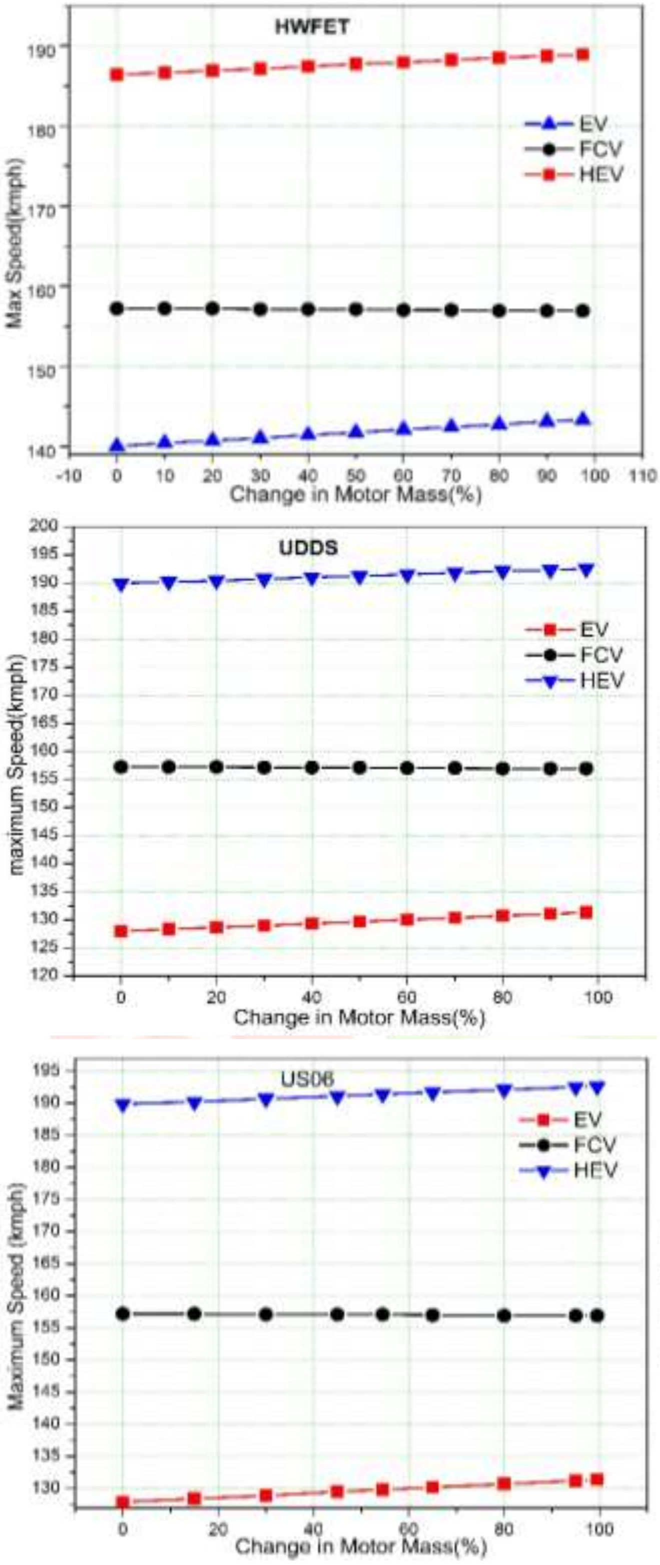

Fig. 6. Changes in maximum speed of the vehicles with changing motor mass

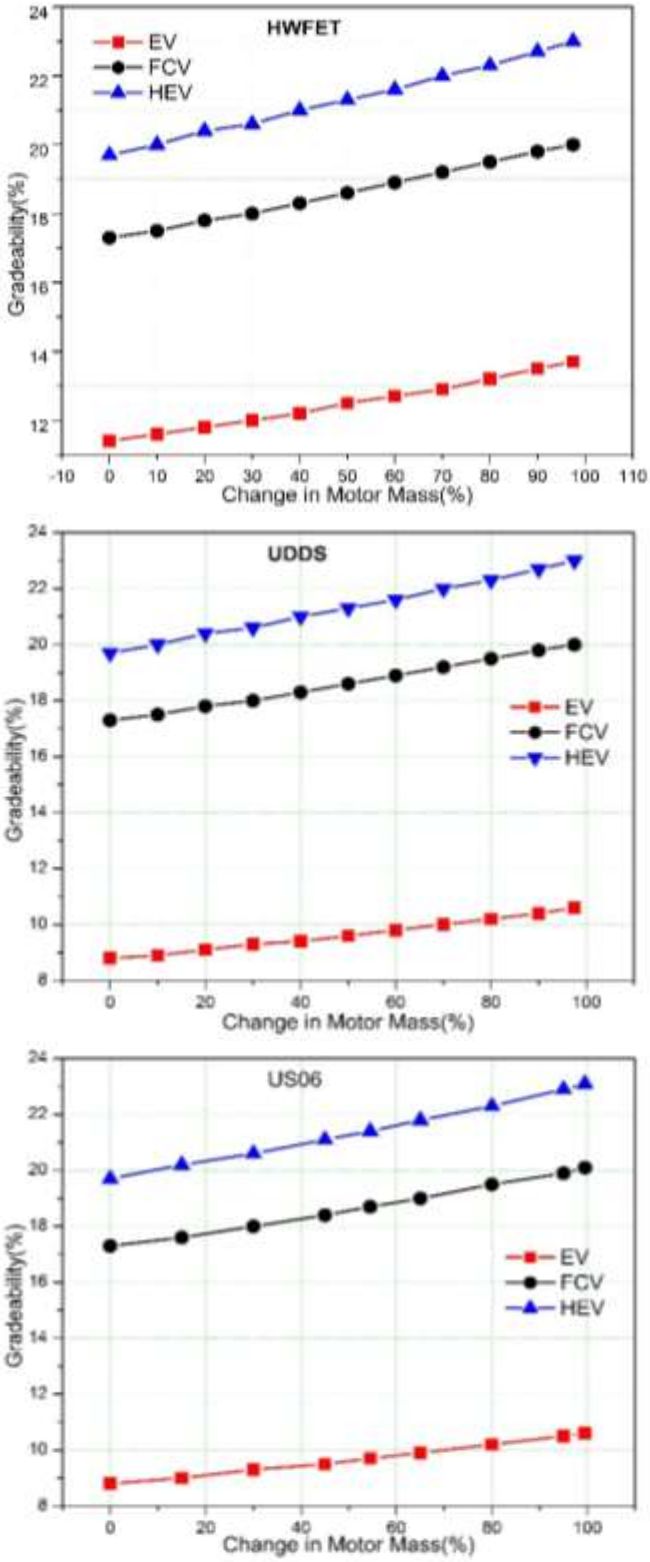

Fig. 7. Effect of motor mass on the gradeability of the vehicles

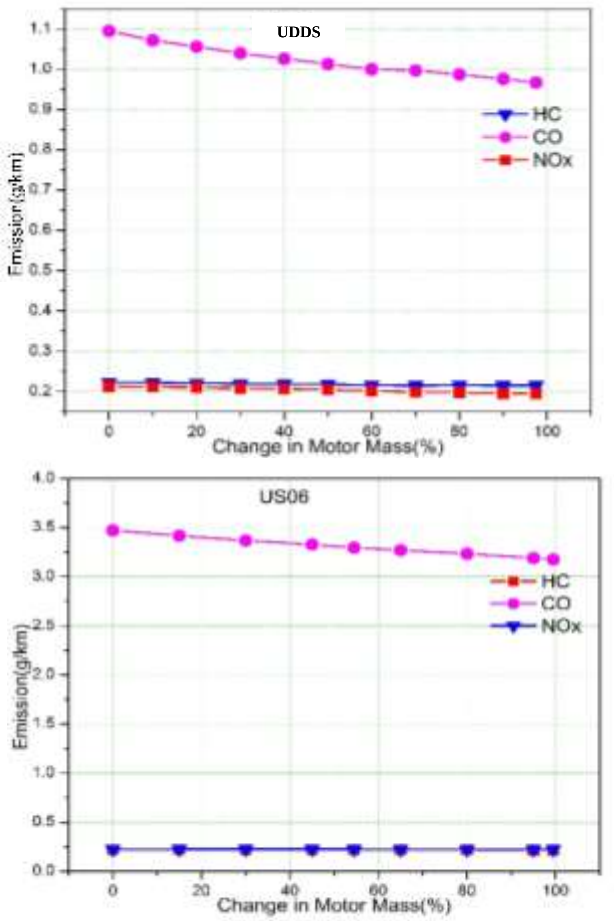

Fig. 7. Effect of motor mass on vehicular emission of HEV

IX.CONCLUSION

Future is of state-of-art transportation system. Number of cars and smart cars are now the status symbol in developed countries. Every year large number of cars and other vehicles are added to the transportation system. This increases the vehicular pollution, energy consumption and scrape. It also increases the consumption of materials used in manufacturing the vehicles. Sustainable development is the global target. Governments' bodies around the world are making stringent policies to control the tailpipe emission of the vehicles. EV, FCV HEV, PHEV and PEV are promoted by providing subsidies. Sustainable, environment friendly and energy efficient vehicular system is possible with the help of new technologies in the field of chemical engineering, material science, electronics, mechanical and electrical engineering and many different areas. Countries like china and USA are even targeting the weight reduction of the vehicle in their policies. Light weighing a vehicle is also essential to make space inside to accommodate other things like AC, audio and video system, extra leg space etc that are necessary from consumer point of view.

This paper discussed, with the help of drive cycle tests of EV, HEV and FCV, the effect of traction motor mass reduction on the performance of the vehicles. the acceleration, speed and gradeability performances can be improved by reducing the motor mass of the vehicle but EV has higher rate of improvement in all field and FCV has problem of on the heavy wheel fuel converter FCV even shows reduction in maximum speed with motor mass reduction. This reduction violets the basic theory that the reduction of vehicle mass improves the vehicle performance. Again the reduction in motor mass does not improve tailpipe emission in all respect. The drive cycle tests conducted on paralle HEV shows increase in NOx emission at high speed with motor mass reduction.

Table4
Percentage reduction in tailpipe emission with 50% reduction in motor mass for parallel HEV

Drive Cycle	Hydrocarbon	CO	NOx
US06	1.7937	5.0979	-0.4444
UDDS	2.2422	7.4885	3.7558
HWFET	2.9069	6.4045	3.9773

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