Performance Evaluation of a Low Cost Series Hybrid Electric Vehicle

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Abstract

The escalating amount of vehicles on the road has raised awareness to vehicular environmental impacts and sustainability; this has provided a stimulus for future mobility considerations. The conventional car may not meet future requirements regarding noise, emissions and energy consumption. There is a distinct lack of short-term alternative solutions that meet consumer requirements and has a potential for mass production. Furthermore, the internal combustion engine has been developed over 100 years and there may be some risk that the automotive companies choose to invest into the "wrong" alternative.

This paper presents a development process in an attempt to find answer this dilemma. The first consideration is the vehicle performance criteria that take into account consumer expectations and operational/regulatory/environmental factors. Secondly, the drive train components are identified, most are commercially available, and are particular to these factors. Finally, a computer simulation is used to assess the performance of the vehicle, in comparison with the factors.

The result of these investigations is a series hybrid electric vehicle that is recharged from the mains. The fuel consumption is four times better than that of a comparable car, but vehicle mass and cost have not increased significantly. The driving range of this vehicle is not limited to the battery-capacity.

This vehicle meets the consumer expectations as well as environmental issues and benefits with added driver comfort. Still being low-cost, it provides the potential for mass-production and thus reducing overall impacts on the environment.

Keywords: HEV, lithium-ion, energy consumption, vehicle performance, cost

1. Introduction

Cars have improved significantly over the last 100 years. They became more versatile, better in performance and more comfortable without increasing the purchase cost, which has lead to unprecedented increase in the number of vehicles on the road, especially given recent changes in work practices that require increase individual mobility. This increase in the number of vehicles together with rising awareness of their environmental impacts and sustainability provided stimulus for current discussion on future mobility.

Conventional cars with internal combustion engine do not meet future requirements regarding noise, emission and energy consumption. On the other hand, electric vehicles, which have far less impact on the environment, do not meet customer requirements regarding range, versatility or cost. Exisiting, mostly parallel, hybrid electric vehicles are too expensive and fuel-cell vehicles still need considerable development of the technology and infrastructure [1] [2]. All recent developments on hybrid electric vehicles have concentrated on the parallel hybrid. The series hybrid electric vehicle has in general been considered to be inferior to the parallel [3].

This paper is concerned with an evaluation of a plug-in series hybrid electric vehicle (mainly for urban and extra urban driving), which design is based on 1) a careful evaluation of vehicle specifications that meet consumer aspirations, and 2) a careful selection of drive train components. The proposed drivetrain concept ensures peace-of-mind concerning environmental impacts like in a pure electric vehicle and peace-of-mind concerning range and versatility like in a conventional car without sacrificing the affordability.

The paper firstly discusses vehicle performance criteria taking into account consumer expectations and operational/regulatory/environmental factors. Secondly, the drive train components, mostly commercially available, are specified in the light of these specifications. Finally, computer simulation is used to assess the performance of the vehicle in comparison with the specifications.

2. Vehicle Performance Criteria

The proposed vehicle specification is based on the following considerations:

Speed: The maximum design speed of the vehicle determines the rated motor power and the smallest gear ratio at a given maximum motor speed. The rated motor power in a pure EV determines the battery power and this is known as a major cost issue. In the proposed vehicle, the rated motor power determines the generator and engine power as well.

To achieve higher speeds in this type of HEV, the five main and costly components (battery, power-electronics, motor, generator and engine) need to be more powerful and as a result bigger, heavier and more expensive. The maximum design speed of the vehicle should be chosen carefully and preferably as small as possible without compromising comfort. The UK has a speed limit of 70 mph (112 km/h) and our vehicle is designed for this speed.

Gradeability: The road gradient on highways together with the maximum speed determines the rated power requirement of the motor. Maximum road grade on UK highways is 4%. The maximum gradient in general determines the highest gear ratio. Most hills have less than 20% gradient and signs will warn before choosing a route with higher gradients. The vehicle is designed to climb at least 20% with maximum mass to make it versatile.

Acceleration: The acceleration determines the maximum motor torque and the gear ratios layout. We use axial air-gap permanent magnet brushed DC motors, which are capable of producing constant torque over their speed range, with about 50% overload torque capability.

It is assumed that the chosen motor that can achieve the maximum speed at highway gradient is powerful enough for moderate acceleration in urban areas. The simulation results presented later in this paper show that the acceleration performance is satisfactory.

Driving Range: Most trips are short trips: about 80% of all travelled distance is less than 40 km each trip [4] [5]. To keep the battery in an efficient range for this distance, the state of charge (SOC) should remain above 20% even when the battery is close to its end of life (80% of rated capacity). As a result, the vehicle should at least manage to achieve 40 km / $(0.8 \cdot 0.8) \approx 60$ km in pure electric mode. The Peace-of-Mind energy management will start the generator automatically to extend the driving range to at least 300 km.

Noise: This vehicle is designed for short trips. These trips usually have a low average speed. At low speeds the engine noise of conventional cars is much higher than the noise of tyres and air-resistance [6]. The electric motor itself is very quiet and the Peace-of-Mind energy management will ensure that the combustion engine does not run when engine noise has major impacts. The vehicle mass will be kept small to decrease tyre noise at higher speeds as well. Thus, this vehicle has very low noise impacts.

Pollution: This vehicle is basically an electric vehicle, powered by a battery. This type of vehicle has no local pollution and no pollution in general if powered with green electricity. The combustion engine will only cut in if necessary to achieve the desired trip distance or the desired power. The

Peace-of-Mind energy management will also assure the engine to run as rarely as possible and in its best efficiency/pollution region. It also avoids cold starts to keep the level of pollution low.

Vehicle size: Though a smaller vehicle keeps impacts low in urban driving and seems to be satisfying for short trips, we use a Daewoo Matiz (see figure 1) for better comparison with actual products.

Figure 1: Daewoo Matiz

Handling/Comfort: We propose to convert a vehicle similar to the Daewoo Matiz and thus the handling and comfort will be at least to the same standard. The conversion will enhance the handling through a better weight distribution. As a result, power steering is not essential any more. Less gear changing, no clutch, less motor noise and vibrations will increase comfort especially in urban driving with many start-stop procedures. Air-conditioning will not be implemented due to its high energy-consumption. Most "eco-cars" like VW Lupo 3l or GM Corsa Eco do not provide this feature either. Nevertheless, it could be implemented with a switch-off facility and powered by gas or even from a larger battery.

Energy Consumption: The aim is to keep the energy consumption between 1 … 2 $^{l}/_{100km}$ of fuel equivalent in urban driving. The vehicle will be purely battery powered and recharged from the mains in this scheme. The extra urban consumption will be higher due to the higher drag losses at higher velocities and because the engine will cut in to provide the power or range. The aim in this scheme is about 3 $^{l}/_{100km}$. This vehicle is designed for mainly short trips and thus, the combined consumption is near to the urban driving consumption and will be below 2 $^{l}/_{100km}$.

Vehicle Mass: The vehicle mass has major impacts on most requirements mentioned above. Keeping the mass low means better gradeability, acceleration, range, less noise and less energy consumption. The aim is to keep or even reduce the vehicle mass, when compared to the original by choosing the heaviest components such as battery and engine as small and light as possible. The motor and generator to be used are permanent magnet DC motors with very high power/mass ratio.

Cost: The purchase cost is targeted to be similar to a conventional vehicle by trying to keep the technology simple and the battery small. The battery is the major cost factor and thus, the battery management ensures highest possible life expectancy of the battery.

In conclusion: The task is to design a mainly battery powered vehicle with very low energy-consumption, pollution and noise but for a competitive purchase price and with high driving range and acceptable performance.

3. Component Specifications

This paragraph derives the component specifications from the vehicle criteria. The following formula are used to estimate the power requirements:

Rolling resistance: $$P_r(v) = c_r \cdot m_{\max} \cdot g \cdot v \qquad (1)$$

Air drag: $$P_{air}(v) = c_d \cdot A_f \cdot \tfrac{1}{2} \cdot \zeta \cdot v^3 \qquad (2)$$

Gradient demand: $$P_{grad}(gradient, v) = m_{\max} \cdot g \cdot v \cdot \sin(\arctan \tfrac{gradient}{100}) \qquad (3)$$

The following constants have been used:

Gravitational acceleration: $g = 9.81 \, {}^{m}\!/_{s^2}$

Air density at 1 bar and 20 ºC: $\zeta = 1.19 \, {}^{kg}\!/_{m^3}$

The total motor power to propel the vehicle at a certain speed v and a gradient is:

$$P_{mot}(gradient, v) = \frac{P_r(v) + P_{air}(v) + P_{grad}(gradient, v)}{\overline{\eta_{mech}}} \quad (4)$$

Mechanical drivetrain efficiency is assumed to be on average: $\overline{\eta_{mech}} \approx 0.9$

The chosen vehicle is similar to a Daewoo Matiz [7] with its small mass. The vehicle body attributes are:

Air drag coefficient: $c_d = 0.32$ (estimated)
Frontal area: $A_f = 2.01 \, m^2$ (estimated)
Tyre rolling coefficient: $c_r = 0.009$ (Advisor file [8])
Mass: $m = 778$ kg (Daewoo Matiz)
Maximum mass: $m_{max} = 1153$ kg (Daewoo Matiz)

Figure 2 shows the power requirements to overcome the rolling resistance, the air drag, the gradient of 4 % and the total required motor power over speed.

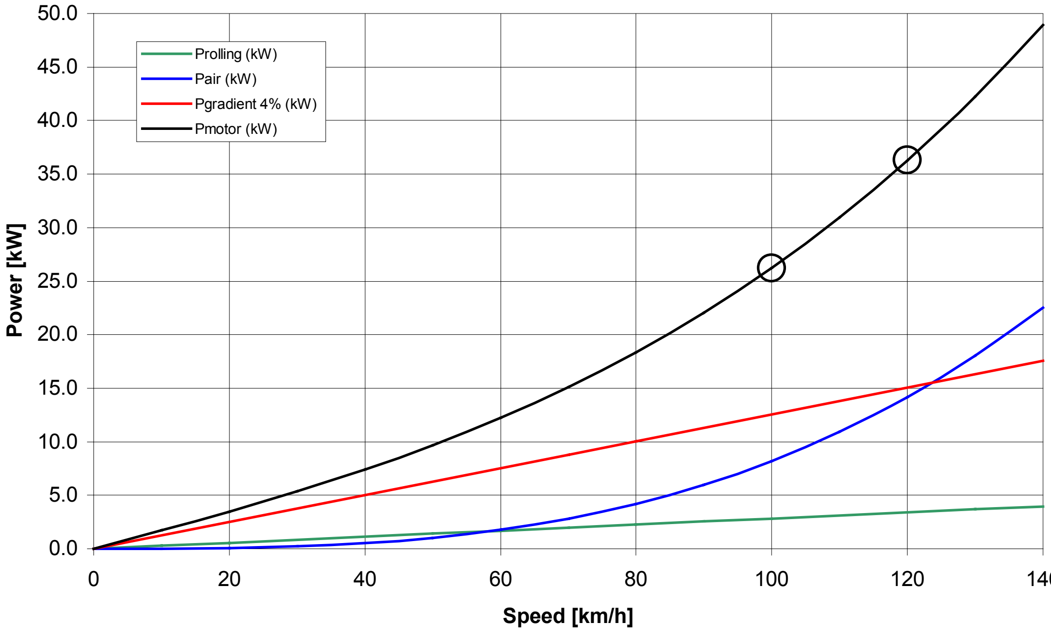

Figure 2: Power Requirements over Speed for the chosen Vehicle with 4% gradient

Propulsion motor requirements:
The power requirement of the electric propulsion motor is determined by the maximum speed and the maximum gradient at this speed. The maximum gradient on UK highways is 4 % = 2.3º. The designed maximum speed is 120 ${}^{km}\!/_{h}$. All calculations are undertaken with maximum mass m_{max}. To achieve 120 ${}^{km}\!/_{h}$ with 4% gradient, the propulsion motor power requirement is:

$$P_{mot}(4\%, 120\,{}^{km}/_{h}) \approx 36kW \text{ (see figure 2)}$$

The chosen motor is a permanent magnet motor with axial air gap and pancake design. The purchase cost of this motor type has a strong relation to the motor power due to the speed limitation and the cost of rare-earth magnets.

Motor size and cost may be reduced if the speed demand is relaxed. At a 4% highway grade a crawling-lane for lorries will be implemented, the average speed is limited to less than 112 ${}^{km}/_{h}$. If the vehicle is designed to run 100 ${}^{km}/_{h}$ with this 4% gradient it will still meet the requirements, but allow for a smaller propulsion motor:

$$P_{mot,cont} = P_{mot}(4\%, 100\,{}^{km}/_{h}) \approx 26kW \text{ (see figure 2)}$$

This power reduction of nearly 30% helps to reduce the cost remarkably. The 26 kW motor is still sufficient to propel the car at a speed of 120 ${}^{km}/_{h}$. The overtorque capability of about 1.5 of this motor type still allows for short duration gradients of 4% at this speed. For longer gradients, the speed needs to be decrease to 100 ${}^{km}/_{h}$ and a higher gear ratio is necessary to receive maximum power.

The chosen motor is a scaled up version of the Lynch LM200 [9] [10]. The LM200 produces 10kW. The propulsion motor torque is scaled up with a factor of 2.7.The scaled motor produces up to 70 Nm continuous and runs at maximum 3,600 rpm with this load. The brushed DC motor is reliable and control is accurate and simple. The Lynch motor provides very good efficiency (90%) in wide operating region and a very good power/mass ratio of about 1 ${}^{kW}/_{kg}$. High torque and low speed keeps gear losses and noise down. Figure 3 shows the efficiency map for this motor and the operating points in the extra urban driving cycle (EUDC). This simulation result [8] shows that the chosen motor is used in a very good efficiency region. The motor power is suitable for this vehicle.

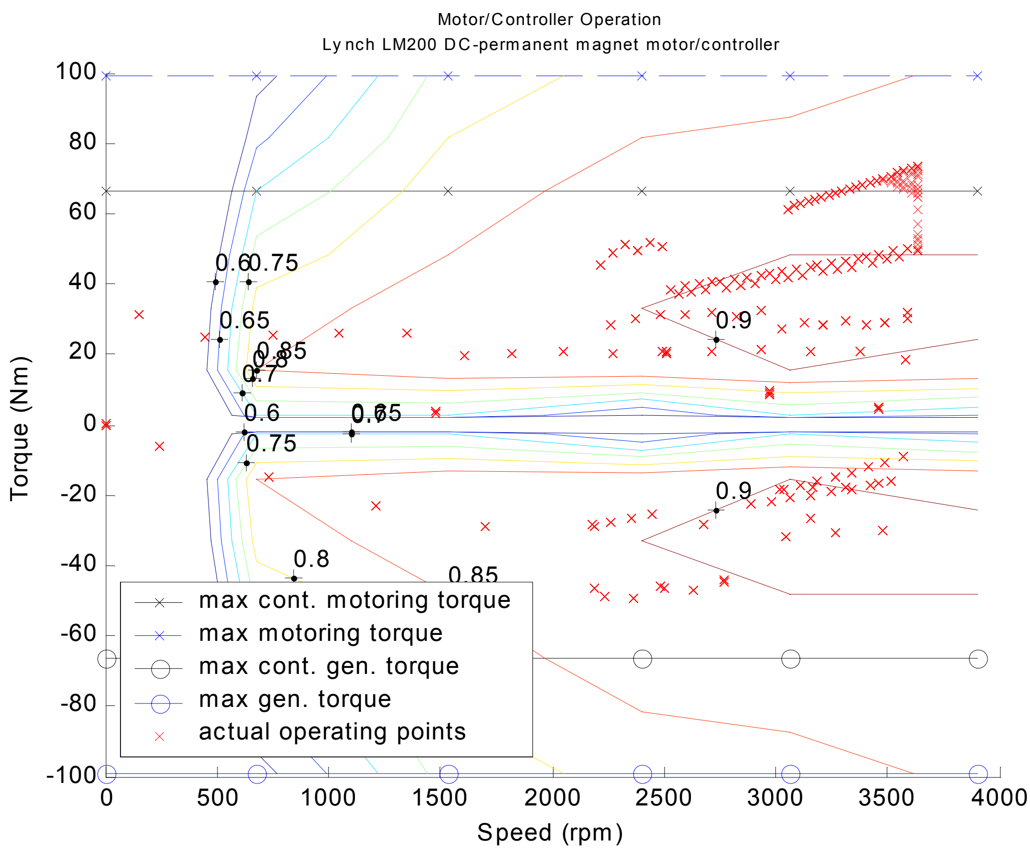

Figure 3: Propulsion Motor/Controller Efficiency Map with Operating Points in EUDC

Engine/generator requirements:
The average power determines the engine/generator power requirement in this series HEV concept. Cruising at 112 $^{km}/_{h}$, the maximum velocity on UK highways, without gradient is assumed to define the average power. The continuous generator output power requirement is:

$$P_{gen,cont} = P_{mot}(0\%, 112\ {}^{km}\!/_{h}) \approx 16.5kW$$

The chosen electric motor, used as a generator is also a scaled up version of the Lynch LM200 with a scaling factor of 1.7. The electric output power is 17 kW with an estimated efficiency of 85% the mechanical input power is 20 kW. This is the minimum continuous engine power requirement.

$$P_{engine,cont} \approx 20kW$$

This vehicle concept is designed for urban driving with mainly short trips. The generator and engine aim to increase versatility and Peace-of-Mind for the driver: no need to think and worry about battery state-of-charge. Thus, the engine is designed to run only rarely and only when noise, vibrations and emissions play a minor role. A cheap, small, lightweight engine can be chosen. For example, a 350 cc four-stroke scooter engine size is sufficient to produce 20 kW. But in this study, the Advisor SI-30 engine is chosen and scaled down to 20 kW for simulation purpose. Figure 4 shows that in this engine, the maximum power point equals to the maximum torque point with good efficiency at this point as well.

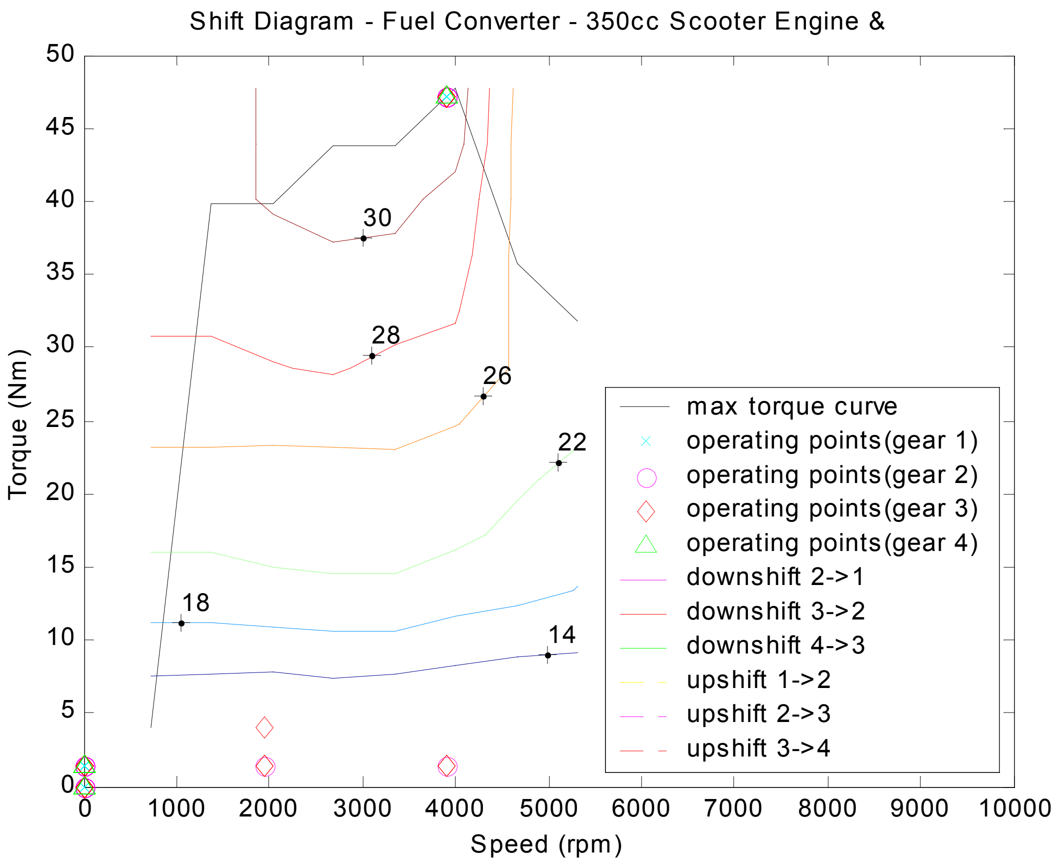

Figure 4: Engine Efficiency Map with Operating Point

Energy storage requirements:

There are two main energy storage requirements: Energy capacity and maximum power. The energy capacity should be sufficient for 60 km urban traffic in pure electric driving mode. The average velocity in cities is about 30 $^{km}/_{h}$. In simplified calculation, we assume an average of 50 $^{km}/_{h}$ for taking the frequent starts and stops into account. The motor power to propel the vehicle at this speed is:

$$P_{mot}(0\%, 50\ {}^{km}\!/_{h}) \approx 2.7kW$$

Assuming a motor/battery efficiency of about 60%, the required energy storage capacity is at least:

$$E_{storage,\min} = \frac{60km}{50\ {}^{km}\!/_{h}} \cdot \frac{2.7kW}{0.6} \approx 5.4kWh$$

The battery power should be sufficient to boost the propulsion motor to its highest power, when the generator runs. Maximum motor power is 1.5 times continuous motor power.

$$P_{storage,\max} = 1.5 \cdot P_{mot,cont} - P_{gen,cont} \approx 22kW$$

The chosen battery type (Li-Ion) is capable of discharging currents that equal to 3 times the rated capacity. The energy storage capacity is determined by this requirement:

$$E_{storage} = \frac{P_{storage,\max}}{3} \cdot h \approx 7.5kWh$$

A modern Li-Ion battery (Thunder Sky TS-LP8582B) [11] has been chosen to keep the battery size and mass low. Li-Ion batteries also provide very good efficiency and good cycle life. Purchase cost has recently become competitive (400 $^{US\$}/_{kWh}$). A comparatively small voltage of 72V, but high capacity of 110Ah provides the required power and energy. Li-Ion batteries essentially need single cell observation. A smaller cell number in a series connection has fewer problems with cell-imbalances and expensive battery management systems. Figure 5 shows the chosen battery with a mass of 60 kg and a comparable lead-acid battery with about 250 kg in front of our current test-bed vehicle.

Figure 5: Li-Ion and comparable Lead-Acid Battery

Gear ratio requirements:

Different gear ratios will be necessary to allow for maximum speed of 120 $^{km}/_{h}$ on one hand and good gradeability of 20% on the other. Table 1 draws the conclusion of the gear ratio calculations:

	1st gear	2nd gear	3rd gear	4th gear
Max. speed	36 $^{km}/_{h}$	60 $^{km}/_{h}$	100 $^{km}/_{h}$	120 $^{km}/_{h}$
Max. grade	20%	11%	4%	1.7%
Total ratio	10.5	6.3	3.8	3.2
Purpose	Hill climbing	Urban driving	Extra-urban	Motorway

Table 1: Gear-ratios and Performance

The vehicle can be driven in 2nd gear only without changing gears in urban driving cycle. This means good acceleration and comfortable, smooth driving. The gearbox loss characteristics are taken from TX_VW Advisor file. The wheel information like losses and rolling-radius are taken from WH_SMCAR Advisor file. Figure 6 shows the gear ratio changing when accelerating from 0 … 120 $^{km}/_{h}$. The strategy is to shift into next gear when maximum motor speed is nearly reached. The motor is most efficient at high speeds as shown in figure 3 and remains quiet.

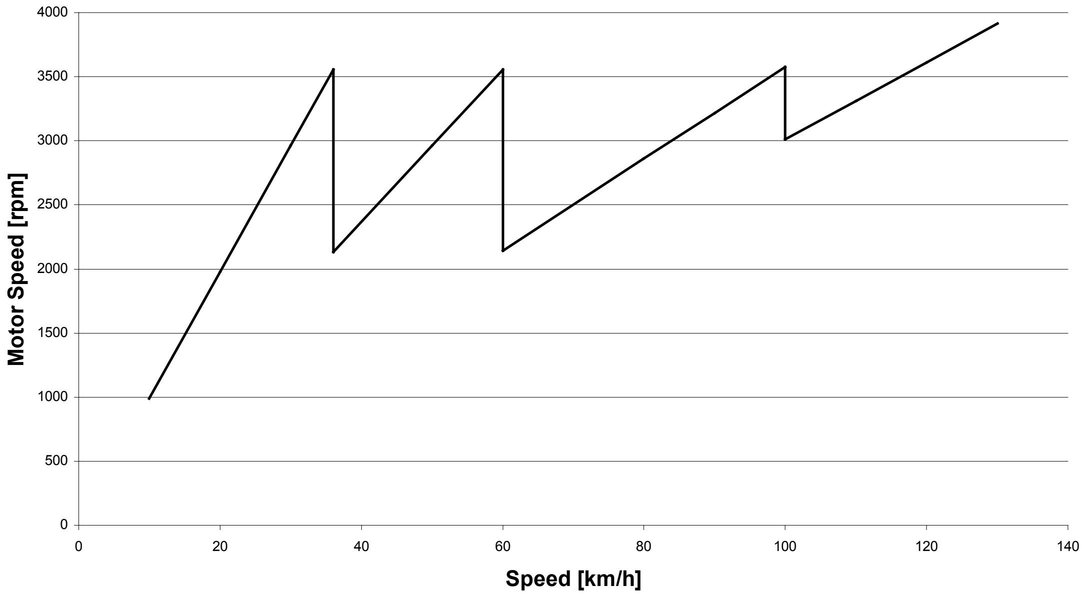

Figure 6: Gear-shifting table: Motor Speed over Vehicle Speed

4. Advisor Simulation

The above calculations helped estimating component specifications. Components and the vehicle have been modeled in Advisor2002 [8] to show that the vehicle meets the requirements. Advisor is a backward-looking Matlab based vehicle simulation program. Vehicle, drivetrain configuration and components can be modeled and run through different standard driving cycles. Different results like loss plots, operating points versus time, operating points in efficiency maps, all sorts of model-variables versus time and average values can be visualized.

Simulation results can be summarized as follows:
1. Maximum **velocity** of 120 $^{km}/_{h}$ can be achieved. Average speed of 112 $^{km}/_{h}$ can be achieved without battery depletion.

2. The **acceleration** results are presented in comparison to the Advisor results for the inbuilt model of th Toyota Prius HEV. The Peace-of-Mind HEV will undertake this simulation test in full-power hybrid mode with engine/generator switched on.

Test	Toyota Prius	Peace-of-Mind HEV
0 – 50 km/h	5.8 s	5.1 s
50 – 100 km/h	10.4 s	12.4 s
Max. acceleration	3.4 m/s^2	3.6 m/s^2

Table 2: Acceleration results in comparison with Toyota Prius results

Table 2 shows, that Peace-of-Mind HEV can achieve very good acceleration in urban driving, even better than a Toyota Prius. In extra urban driving, the acceleration is still acceptable.

3. **Gradients** of 4% can be achieved at 100 $^{km}/_{h}$ with maximum cargo over long duration. 4% at maximum speed for short duration is possible.

4. **Acceleration** in urban driving is sufficient to follow ECE-15 driving cycle in pure electric mode and in 2nd gear without gear shifting.

5. The **fuel consumption** in 180 km extra urban driving (26 EUDC cycles) is 3.6 $^{l}/_{100km}$ fuel equivalent. In urban driving (ECE-15) the Advisor result is 1.1 $^{l}/_{100km}$ fuel equivalent. With an average charger efficiency of 80% this is less than 1.4 $^{l}/_{100km}$. The total fuel consumption (20% EUDC 80% ECE) in combined consumption is about 1.8 $^{l}/_{100km}$ compared to the 7.3 $^{l}/_{100km}$ of the Daewoo Matiz.

6. The pure electric **range** in urban driving is 89 km (ECE-15) and about 70 km in a very good battery efficiency region. The hybrid mode range is limited to the fuel tank capacity only.

7. The total vehicle **mass** is 779 kg compared to the 778 kg of the original Daewoo Matiz.

8. **Cost** has not been modeled and simulated, but the concept tries to keep it as low as possible. The extra urban driving cycle (EUDC) showed that average power need is only about 7 kW. Reducing the engine/generator power to a level of about 10 kW could further decrease cost and extra urban fuel consumption, but will lead to battery depletion mode when running at full speed over long periods of time.

5. Conclusion

This paper demonstrates that using electric propulsion in vehicles can reduce energy consumption and other impacts like noise or local air-pollution without increasing vehicle mass or decreasing versatility and comfort. The only contribution is limiting the maximum speed to a reasonable value that equals to national speed limits in most cases. The series hybrid electric drivetrain concept makes sense in this type of vehicle, where the average power requirement is low. The fuel economy is about 4 times better than in a comparable vehicle without sacrificing performance, comfort, versatility, safety or affordability. Other impacts like noise and emissions are decreased.
The discussed peace of-mind-vehicle concept is implemented in our test vehicle and the energymanagement will be developed. Real world tests and driving will be compared to the simulation results.

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