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Effect of Transmission Design on Electric Vehicle (EV) Performance

Q. Ren, D.A. Crolla and A. Morris

Institute for Automotive and Manufacturing Advanced Practice (AMAP), University of Sunderland, Industry Centre, Sunderland SR5 3XB, UK

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Abstract: The aim of this paper is to develop a simple EV model and predict its energy consumption with a variable and fixed ratio gearbox over a standard driving cycle in order to understand whether this could offer significant efficiency gains. The powertrain of a generic electric vehicle was modelled in Matlab / Simulink using the QSS Toolkit. The electric vehicle was then fitted with different transmissions with different levels of complexity. Simulations were done to investigate the energy consumptions across 6 standard driving cycles. The emerging conclusions are that it is possible to improve overall energy consumption levels by around 5 to 12 % with a variable ratio gearbox depending on the driving cycle used. However, there are many other practical considerations which must be weighed against this positive result – and the paper discusses the impact of several of these such as, gearbox efficiency, additional weight, cost and complexity, effect on drivability and potential for motor downsizing.

Key words: Electric vehicle(EV), transmission, efficiency.

1. Introduction

The current level of interest in Electric Vehicles (EVs) could hardly be overstated as manufacturers and governments around the world appear to have increased interest at a staggering rate [1]. The historical perspective of EVs is a fascinating engineering story; few people realized that they pre-dated Internal Combustion (IC) engine powered vehicles and were commercially available at the end of the 19th century [2]. An electric car even held the world land speed record in 1899 and was the first car to exceed one mile per minute. At this time, for a given power output, one only had to compare the size and complexities of three competing devices – electric motor, IC engine and steam engine – to realise that the electric motor was a clear winner. Nevertheless, the drawback of the electric powered vehicle was the limited energy storage using rechargeable batteries; the specific energy (Wh / kg) of gasoline is around 300 times higher than that of the original lead acid batteries. There are several excellent references [1-5] recounting the story of electric vehicle development up to the present day.

The resurgence of current interest in the early part of the 21st century has been driven by both political and technological developments, namely a requirement to control global emissions and the emergence of new battery designs with improved specific energy, energy density and rechargeability properties [3].

The vast majority of current EV designs to date have used a single fixed ratio transmission – often incorporated in the differential unit [4, 5]. This advantage of the electric motor is helped by the fact that most motors have two ratings – an intermittent high power curve and a lower continuous power curve, normally constrained by heat dissipation. So, high torques are always available for good acceleration, particularly from low speeds, and the vehicle top speed is controlled by the torque on the continuous power

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Corresponding author: Q. Ren, Ph.D., research fields: hybrid electric vehicles, electric vehicles, transmissions, in-vehicle network system. Email: qinglian.ren@sunderland.ac.uk.

curve, so the fixed reduction gear is normally selected to control this.

However, one of the main conclusions to emerge from the plethora of research work into energy efficient vehicles is that it is necessary to pursue every possible avenue for minor efficiency gains. The point is that only when all these gains are added together does the vehicle begin to show worthwhile advantages. A classic case study to underline this conclusion is to compare two contrasting approaches to energy efficient vehicles (i) a full hybrid, e.g. Toyota Prius and (ii) a conventional state of the art diesel vehicle, e.g. BMW118d. The Toyota Prius is a highly sophisticated hybrid design using a combination of an IC engine based on the Atkinson cycle, coupled with two electric motors and a unique epicyclic gearbox. The BMW118d is a conventional vehicle with a diesel engine modified for high efficiencies particularly at part load, a conventional transmission, stop-start arrangement and some regeneration capability. For both these vehicles all the input energy derives from the fuel input – although they have very different ways of managing the efficient usage of it – but crucially they both support the key issue that research into energy efficient vehicles depends on the pursuit of all avenues of efficiency gains together.

Returning to the case of EVs, it is therefore of interest to investigate whether it is possible to manage the efficiency of the electric motor, so that by using an intermediate gearbox the motor is operated more often in its higher efficiency region. The aim of this paper is to develop a simple EV model and predict its energy consumption with a variable and fixed ratio gearbox over standard driving cycles in order to understand whether this approach could offer significant efficiency gains.

2. Modelling

The modelling of the electric vehicle performance is done using the QSS Toolkit [6, 7]. This is a quasistatic simulation package based on a collection of Simulink blocks and the appropriate parameter files which can be run in any Matlab / Simulink environment. The vehicle model itself is straightforward and is shown in Fig. 1; it is a conventional plug-in type EV with the addition of a gearbox in the power train

The motor characteristics are intended to represent a typical generic motor of 40kW. They were taken from Larminie [2] who presents a Matlab script to generate a set of generic motor properties based on assumptions about the losses within the motor.

The vehicle parameters are summarised in Table 1; they are intended to be representative of a typical generic vehicle rather than any specific design.

The input to the model is one of the standard driving cycles – the NEDC cycle is used extensively in this work – and the solution procedure is based on stepping through the driving cycle at typically one second steps, calculating the equilibrium condition and then collecting all the data for plotting at the end of the cycle. The modelling assumptions are kept very simple in this initial work, so that no account is included of losses in the gearbox or batteries. Thus, the focus of attention is on the motor efficiency map and the major issue for whether it is possible to improve overall energy usage by operating at or near the best efficiency points.

3. Simulation Results

3.1 EV with Single Transmission Ratio

The first results shown in Fig. 2 refer to the baseline condition of the vehicle with no gearbox. Each point on the map of motor torque vs speed is the solution at a single point during the NEDC cycle; the cycle defines

Table 1 Vehicle parameter data.

Parameter, units	Value
Total vehicle mass, kg	950
Wheel diameter, m	0.5
Aerodynamic drag coefficient	0.22
Frontal area, m^2	2
Rolling resistance coefficient	0.008
Motor maximum torque, Nm	240
Motor maximum speed, rad / s	800
Motor power, kW	40
Final drive ratio	3.5

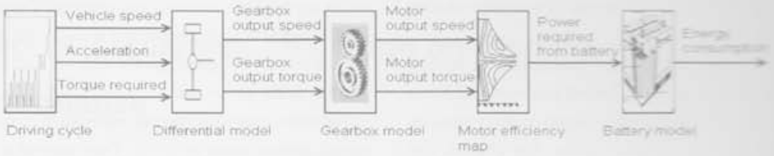

Fig. 1 Block diagram of EV model.

input from t = 50s to t = 1220s, so there are 1170 points on this figure. The top half of the figure refers to conditions in which the motor is delivering power and the bottom half to conditions in which the motor acts as a generator and regenerates power which is fed back to the battery. The efficiency lines in the top half are defined as (input power required / output power delivered); the efficiency lines in the lower half are defined as (power regenerated / input power) From 0 to 166.7 rad / s the maximum torque that the motor can deliver is 240 Nm, and after this point the maximum power line is shown.

3.2 EV with Continuously Variable Gearing

The next results assume that the gearbox is infinitely variable so that any ratio can be selected; in fact upper and lower limits are applied so that the ratio can be any value between 4 and 0.6. The calculation procedure is effectively a simplified optimisation strategy. At any point in the drive cycle the torque and speed demanded by the motor are first calculated. Then, this power requirement a search routine is used for the motor map to find the point of maximum efficiency and the appropriate selected gear ratio so that the motor can operate at this point and still deliver the necessary torque and speed to the driving wheels. It is further assumed that -the gearbox response would be fast enough to follow these changing requirements. Thus, the results shown in Fig. 3 effectively describe the optimisation of the motor usage over the selected NEDC drive cycle. It is clear from Fig. 3 that the results follow the nominal line of maximum efficiency of the motor. The gear ratios selected by the algorithm to achieve this are shown in Fig. 4.

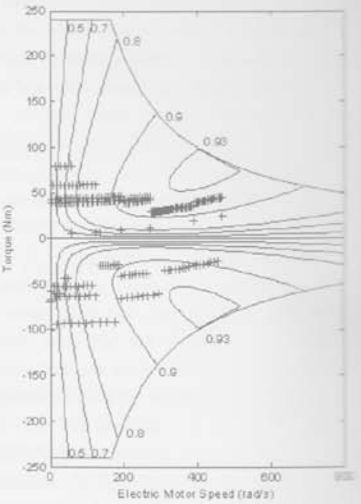

Fig. 2 Motor operation points with no gearbox.

3.3 EV with a Multispeed Gearbox

The results shown in Fig. 5 refer to the case in which it is assumed that a four speed gearbox is fitted in the transmission. The ratios are selected in a rather subjective fashion after inspection of Fig. 4, and are 2.5, 1.5, 1 and 0.8. In practice, the gear ratio selection would be done automatically rather than manually as with a conventional IC engine car. Here, a simplistic gear selection strategy is used:

For constant speed running the highest gear (lowest numerical ratio) is selected.

When accelerating, the ratio is based simply on speed – such that the above ratios are selected for the speed ranges 0-100, 100-200, 200-300 and 300-800 rad/s.

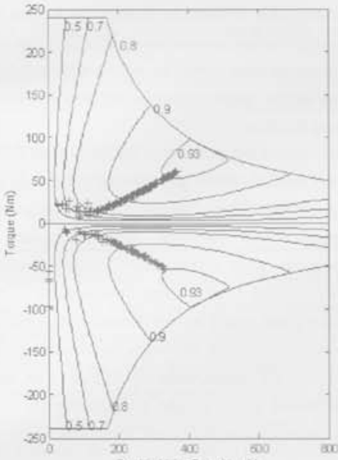

Fig. 3 Motor operation points with continuously variable gear.

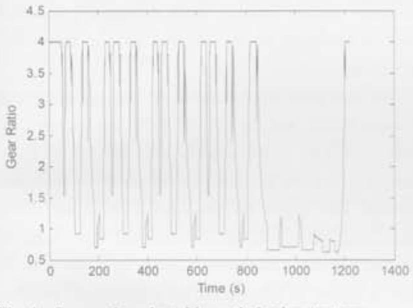

Fig. 4 Gear ratios selected by optimisation strategy.

It is not suggested that this is optimal, but this approach is chosen to understand the sensitivity of the energy usage predictions to practical design issues.

The results are then repeated for two other gearboxes:

3 speed with ratios of 2, 1 and 0.8, 2 speed with ratios of 2 and 0.8 for the speed ranges 0-300 and 300-800 rad / s, and the motor operation points for the 2 gear system are shown in Fig. 6.

The results are summarized in Table 2 showing the relative energy consumptions for the different geared systems over the NEDC cycle. The improvements resulting from fitting an additional gearbox are actually rather modest over the NEDC cycle. The percentage improvements would, in practice, be immediately cancelled out by the additional efficiency losses in the gearbox itself, which have initially been ignored in this work. One of the potential advantages of a geared transmission relates to possible improvements in drivability. For example, the 0 to 100 km / h acceleration time of the fixed gear vehicle is 18.3 s, whereas with just 2 gears, this time is reduced to 12.4 s. The top speed of 183 km / h of course remains unchanged.

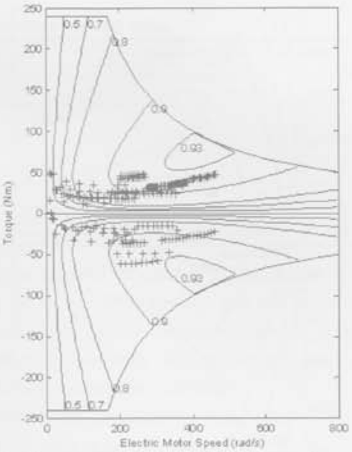

Fig. 5 Motor operation points with four gear ratios.

This raises the possibility that one of the advantages of a simple geared system would be to downsize the motor, but still retain the same drivability characteristics. Whether this is a practical proposition will depend largely on the specific vehicle application, and the detailed properties of the motor selected relative to the critical vehicle properties of mass, rolling resistance and aerodynamic drag. For example, although the NEDC is widely used as a standard driving cycle, the peak power demanded from the motor is only 21.9 kW. In practice, the peak power of

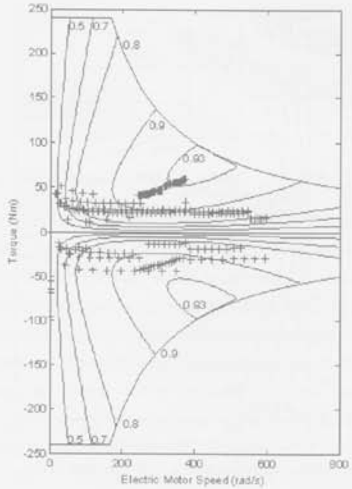

Fig. 6 Motor operation points with two gear ratios.

Table 2 Efficiency improvements for different gearboxes over the NEDC cycle.

	Energy consumption per 100km (kWh / 100km)	Improvement %
no gear	8.33	-
CVT	7.89	5.28
4 speed	7.96	4.45
3 speed	8.01	3.76
2 speed	8.10	2.71

the motor would have to be around double this value in order to provide a sufficiently high level of acceleration to meet customer demands.

3.4 Effect of Drive Cycle

One of the fundamental problems now facing the automotive industry in their quest to develop energy efficient vehicles is a methodology which enables robust comparisons of competing designs. The approach adopted to date has largely depended on standard driving cycles. This is defensible from a scientific point of view because vehicle designs are then compared under like-for-like input conditions. But one of the major issues is then what exactly constitutes typical driving cycles which somehow represent normal everyday driving? Inevitably, this has led to the development of many so-called standard driving cycles – and these to some extent do reflect different driving patterns in the three major world markets: Europe, USA and Far East.

Some idea of this problem is highlighted in Table 3, in which the EV results are repeated for six different driving cycles. These results are somewhat more promising. Over four of the six cycles, the improvement using continuously variable gearing is between 9.6 and 12.4%. Even though some of these efficiency gains would be lost through the losses in the transmission, there are still some worthwhile gains to be exploited. Of course, these would also be set against the additional cost, weight and complexity of the transmission system. However, small efficiency gains of this order would be seriously considered in IC engined vehicles – as part of the relentless quest for any efficiency gains possible. Hence, it is likely that as electric vehicles become more common, companies will be searching for all potential ways of improving efficiency.

The two most representative driving cycles are the Europe NEDC and the USA FTP-75; the Europe City and USA City 1 are actually only subsets of these longer cycles and the Japan cycles are rather short and simple. The results for the USA FTP-75 are rather promising; this cycle has less constant speed running and include more acceleration cycles up to the 40 to 50 km / h region. So the effect of the continuously variable gearbox over these conditions is to offer a greater improvement.

3.5 Effect of Drivability

Finally, one of the challenges facing the industry is temptation to optimise their design around achieving a top result in the driving cycle test – thus resulting in leading headline figures for fuel economy and carbon dioxide usage. Overall, this is clearly not a desirable situation – when the nature of the test procedure actually drives the engineering development of the vehicle. It also raises another major area for research

Table 3 Comparisons of improvements in energy consumption over 6 different driving cycles.

Driving cycle	No gearbox	4 speed gearbox		Continuously variable gearbox	
	Energy consumption per 100km (kWh / 100km)	Energy consumption per 100km (kWh / 100km)	Improvement %	Energy consumption per 100km (kWh / 100km)	Improvement %
Europe NEDC	8.33	7.96	4.5	7.89	5.3
Europe City	6.87	6.22	9.7	6.12	11.0
USA FTP-75	8.45	7.77	8.0	7.53	10.9
USA City I	9.06	8.43	7.0	8.19	9.6
Japan 11 mode	6.93	6.61	4.6	6.55	5.4
Japan 10 mode	7.20	6.41	11.0	6.31	12.4

into energy efficient vehicles – referred to as 'drivability'. This term is used to cover an extensive range of vehicle properties which result in the drivers' satisfaction levels with the car. Examples of the subjective terms used to assess drivability are; idle conditions, launch feel, 'throttle' response and feel, cruise stability, tip-in, tip-out, shunt oscillations, brake feel and brake blending with regeneration etc. There is clearly a future research opportunity to investigate whether there are robust relationships between measurable vehicle properties and the subjective assessments of drivers.

4. Conclusions

The modeling and analysis to obtain these results was intentionally kept simple in order to explore whether there were any potential improvements in efficiency obtainable by using a geared transmission in an electric vehicle.

Several conclusions may be drawn, some more positive than others:

Using the NEDC cycle the efficiency improvement assuming a continuously variable gearbox is fitted is only 5.3% for the typical generic vehicle used. In practice, the losses in the transmission would counteract these gains, so the net result would be zero.

However, using the USA FTP-75 cycle which has a different balance between accelerating and constant speed running, the gain is predicted as 10.9% - a much more promising figure even accounting for transmission losses.

Other potential benefits of a transmission system may be in overall drivability and the potential to downsize the motor somewhat whilst retaining acceleration capability for the limited times that maximum acceleration is required.

Overall, this simplified modeling suggests that the idea of using a geared transmission in an electric vehicle is worthy of further research using a more sophisticated driveline model and attempting to quantify both efficiency gains and drivability improvements.

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