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Modelling and Analyzing Electric Vehicles with Geared Transmission Systems: Enhancement of Energy Consumption and Performance

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Abstract

The main aim of this paper is to study the potential impacts in performance and energy consumption by utilising a geared transmission in electric vehicle driveline. This is achieved by modelling and analysing the powertrain of a generic electric vehicle using Matlab/Simulink-QSS Toolkit, with and without a transmission system of varying levels of complexity, to investigate whether the addition of a gearbox results in significant values of predicted efficiency gains. Predicted results are compared for a typical electrical vehicle (EV) in three cases: without a gearbox, with a continuously variable transmission (CVT), and with a conventional stepped gearbox. Predictions are made over the standard driving cycles. One of the critical features in this paper is the usage of the electric motor in its region of high efficiency. Consequently, two motors are modeled in this work in order to understand the sensitivity of the results to the assumptions about motor efficiency maps. These motors will be referred to as a theoretical motor derived from generic equations and a practical motor which is effectively a look-up map from the manufacturers' data. The results showed that it is possible to improve overall performance and energy consumption levels using a continuously variable ratio gearbox.

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Keyword: Electric vehicle (EV), transmission, modeling and numerical simulations, efficiency and energy consumption, vehicle performance

1. Introduction

There has been a massive resurgence of interest in electric vehicles (EVs) over the past decade. Many observers now see them as the long term solution to reducing vehicle emissions and CO_2 usage in comparison to alternative approaches such as hybrid vehicles, fuel cells or biofuels [1, 2]. The public perception of electric vehicles has changed dramatically and recently announced vehicles such as the Tesla roadster and Chevrolet Volt have reinforced the idea that they are now becoming seriously competitive products. Not long ago, electric vehicles were still seen as niche products and associated more with 'milk float' technology rather than a viable passenger transport alternative [3-5].

The massive advances have occurred in battery technology, although the progress has been gradual and sustained so that it has not commonly been perceived as a major breakthrough. The vehicle range available with modern battery sets such as Lithium Ion is now typically of the order of 200km, which makes electric vehicles acceptable for much urban use. High cost of the batteries is still a problem and despite a relentless downward price trend, the battery sets are often supplied on a leasing arrangement rather than a straightforward purchase.

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As the electric vehicles market continues to grow, the vehicle manufacturers will place increasing emphasis on searching for efficiency gains. This process of continual improvement is central to vehicle development and has occurred for example over recent decades with internal combustion engines; the industry has achieved fuel consumption and CO_2 emissions figures that were considered impossible twenty years ago. In all the green solutions, battery electric cars have the best well-to-wheel efficiency of both conventional cars and hydrogen fuel-cell cars. For example, with 1 MWh of electricity, an EV can drive 5525 km; while using the same amount of electricity to generate hydrogen and to drive a fuel cell car, the distance is reduced to 1790 km [6].

Despite the high worldwide level of interest in EVs some aspects of the vehicle technology have received little attention. The transmission design is one such area and perhaps it is understandable that the majority of research attention has to date focused on the more obvious topics of batteries, motors and power electronics.

This paper focuses on one particular area, the addition of a transmission gearbox, in which efficiency gains may be achievable for electric drivelines. It is commonly argued that one of the distinct advantages of an electric motor as a motive unit is its torque characteristic; it can deliver maximum torque from zero speed and throughout the low speed range – typically up to around 2000 rev/min. then, the available maximum torque reduces with speed along the motor's maximum power curve. This is a much better characteristic than that associated with internal combustion engines, which cannot deliver useful torque at low speeds and because of their relatively narrow torque and power bands must be used with multispeed transmissions in order to deliver tractive power to the vehicle in a suitable form. Typical electric motors have another desirable feature, their maximum intermittent power is considerably higher than their rated continuous power 75kW compared to 45 kW for the example motor used here. The limiting factor is usually related to controlling the amount of heat build-up. Consequently, good acceleration times can be achieved providing they are only used for relatively short periods, a situation which fortunately is typical of normal driving.

However, the efficiency curves for a typical electric motor are highly dependent on both speed and torque. The motor efficiency tails off rapidly at low speeds and torques where its efficiency might drop to say 50%, whereas in its mid speed and torque range it can be as high as 93%. Consequently, it is of interest to the energy efficient vehicle community to try and quantify any potential gains from utilising a gearbox in order to operate the motor for longer periods in its high efficiency region.

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The aim of this paper is to investigate whether there are any potential efficiency or performance benefits for using geared transmissions for EVs. Predicted results are compared for a typical EV without a gearbox, with a CVT and with a conventional stepped gearbox. Predictions are made over the standard driving cycles. Two motors, theoretical and practical, are modeled in this work in order to understand the sensitivity of the results to the assumptions about motor efficiency maps.

2. Electric vehicle modeling

2.1 Vehicle modeling

The modelling of the electric vehicle performance is done using the QSS Toolkit [7]. This is a quasistatic simulation package based on a collection of Simulink blocks and the appropriate parameter files that 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.

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Two types of motors are used in this paper, namely: a generic motor and a practical motor. The generic motor characteristics are intended to represent a typical generic motor of 40 kW. They are taken from Larminie's book [5] who presents a Matlab script to generate a set of generic motor properties based on assumptions about the losses within the motor.

The data of the practical motor are given by UQM [8], an American company that develops and manufactures high-performance, power-dense and energy-efficient electric motors, generators and related power electronics. This motor is selected as being representative of a current, off-the-shelf motor suitable for electric vehicle application.

The input to the model is one of the standard driving cycles, the NEDC cycle and USA FTP 75 are 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. Thus, the focus of attention is on the motor efficiency map and the major issue of whether it is possible to improve overall energy usage by operating at or near to the best efficiency points.

2.2 Method of selecting motor operation point

The schematic diagram of selecting motor operation point is shown in Fig. 2.

For a generic motor, the efficiency of each point is calculated as follows.

For any given point (x, y),

$$Power_{output} = x.y \tag{1}$$

$$Power_{input} = Power_{output} + kc.y^2 + ki.x + kw.x^3 + ConL \tag{2}$$

$$\eta(x, y) = \frac{Power_{output}}{Power_{input}} = \frac{x.y}{x.y + kc.y^2 + ki.x + kw.x^3 + ConL} \tag{3}$$

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where $kc.y^2$, $ki.x$, $kw.x^3$ and $ConL$ are copper losses, Iron losses, windage losses and constant motor losses respectively. In this study, kc, k, kw and $ConL$ are 0.2, 0.008, 0.00001 and 400, respectively.

Let (x_1, y_1) represent any point along the constant power line on which $power = x.y$,

$$x_1.y_1 = x.y \tag{4}$$

$$eta(x_1, y_1) = \frac{x_1.y_1}{x_1.y_1 + kc.y_1^{\ 2} + ki.x_1 + kw.x_1^{\ 3} + ConL} \tag{5}$$

For Equation (5), replace y_1 with $\frac{x.y}{x_1}$, we can obtain

$$eta(x_1, y_1) = \frac{power.x_1^2}{kw.x_1^{\ 5} + ki.x_1^3 + (power + ConL)x_1^2 + kc.power^2} \tag{6}$$

Once the expression of efficiency for any point along the constant power line is given, Matlab can be used to search for the most efficient point.

For the practical motor, the efficiency of each point is obtained via interpolation of data given by the motor manufacturer, so effectively it is input as a look-up table and Matlab is used to interpolate between the data points to find a specific operating condition.

3. Results with a generic motor

The vehicle parameters for the EV with the generic motor are summarised in Table 1; they are intended to be representative of a typical generic vehicle rather than any specific design. The motor rated power is 40 kW, and the total vehicle mass is set to be 950 kg. The input to the model is one of the standard driving cycles – the NEDC cycle is used extensively in this work. 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 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 of whether it is possible to improve overall energy usage by operating at or near to the best efficiency points.

3.1 EV with single transmission ratio

The first results shown in Fig. 3 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 inputs from t = 0 s to t = 1220 s. 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.

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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 in Fig. 3.

In this case, the maximum power line is actually the line for rated power, which is 40 kW. On each point of that line,

$$power = torque \times speed = 40kW \tag{7}$$

This means that if it is run at this power, its temperature will settle down to a safe level. Because it is fairly large and heavy, it takes some time to heat up to a dangerous value. So if in any case more power is needed, it can be run in excess of 40 kW, as long as this is controlled less than about 1 minute. This is extremely useful for a electric vehicle as peak power may only needed for a short period of time, such as when accelerating (Larminie and Lowry 2003).

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 of the motor are first calculated; then, for this power requirement a search routine is used with the motor map to find the point of maximum efficiency and the appropriate gear ratio selected 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. 4 effectively describe the optimisation of the motor usage over the selected NEDC drive cycle. It is clear from Fig. 4 that the results

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follow the nominal line of maximum efficiency of the motor. The gear ratios selected by the algorithm to achieve this are shown in in Fig. 5.

3.3 EV with a multispeed gearbox

The results shown in Fig. 6 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. 5, 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:

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

ii) 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.

It is not suggested that this is in any way 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:

i) 3 speed with ratios of 2, 1 and 0.8

ii) 2 speed with ratios of 2 and 0.8 for the speed ranges 0-300 and 300-800 rad/s

The motor operation points for the 2 gear system are shown in in Fig. 7.

The results are summarized in Table 2 show 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

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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.

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 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

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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 engine 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.

4. Results with the practical motor

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The vehicle parameters for the practical motor are summarised in Table 4. Compared with the parameters used for the previous motor, the vehicle is heavier and has bigger drag coefficient. This is because the data for the motor is from a 75 kW motor, which should be used on a larger vehicle. This does not affect the usefulness of the results, because the primary objective is to investigate the potential benefits of different transmissions in a typical EV application.

The motor data is taken form a commercially available brushless permanent magnet, liquid cooled motor with a peak power of 75kW, peak torque of 240 Nm and rated continuous power of 45kW as a motor and 41kW as a generator. However, the study is based on the assumption that this is typical of the motor characteristics used for vehicle applications. It is not intended to analyse or comment upon the properties of this specific motor.

The model of the vehicle and drivetrain is kept very simple and is shown in in Fig. 1. No account is taken at this stage if the efficiencies of the gears or batteries. The focus of attention is whether it is possible using an additional gearbox to utilise the motor around its high efficiency region and thereby derive some overall energy consumption benefits.

4.1 Results from simulations over the NEDC cycle

4.1.1 No gearbox

The first set of results are all carried out using the NEDC driving cycle; this is remain the most commonly used driving profile used in Europe, although as observed previously considerable controversy surrounds the idea of what are claimed to be 'standard' driving cycles. The NEDC cycle and the resulting torque demand or this vehicle are shown in in Fig. 8.

The first phase of the NEDC cycle comprises four repeats of a 'city' phase, in which there are significant periods of low speed constant running. The second phase is intended to represent 'urban' driving and consists again of substantial periods of constant speed running, this time at higher speeds. The required torque figures at the input to the differential, assuming that the reduction gear would be incorporated here, emphasise the low torque requirement whenever the vehicle is running at constant speed.

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For the conventional arrangement in which there is no gearbox, the choice of single reduction, final drive ratio is important; it is a compromise between acceleration performance, or more generally the whole feeling of drivability, and overall energy usage. Several final drive ratios are tested over the NEDC cycle and the results are shown in Table 5. The ratio of 3.5 is selected on the basis of a fairly subjective judgement of minimising energy consumption whilst retaining reasonable acceleration capability.

The motor operation points with no gearbox are shown in Fig. 9. Each point is the result of an individual calculation at 1s intervals. However, some care must be used when interpreting this graph because in the constant speed running conditions, the required tractive motor torque is constant, and so many points lie exactly on top of each other. Hence, the seven points of low torque, below 25Nm, are actually much more significant than might appear, because each point actually represents several seconds of constant speed running; the exact data can be extracted from Fig. 8. But these points are important in overall energy calculations because they all lie in a region of very low motor efficiency.

Of course, the overall effects on the total energy losses are a combination of the facts that although the motor efficiency is low, so too is the absolute value of torque delivered – hence the overall effect may not be as significant as it may first appear.

4.1.2. Continuously variable gearbox

The NEDC cycle is then repeated assuming a continuously variable gearbox is fitted in the transmission, and the motor operation points are shown in Fig. 10. These are simplified, idealised calculations ignoring at this stage any efficiency losses in the transmission itself.

The calculations are based on the following procedure: for each torque demand sample the gear ratio is calculated which results in the motor torque and speed being optimised in terms of the motor operating efficiency. The calculation requires some interpolation of the motor data points which are shown as joined-up curves in Fig. 10.

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Thus, the overall approach is effectively a simple optimisation procedure, and the results in Fig. 10 show how the points now congregate in the optimum motor efficiency region. In practice, the gear ratio selection is a compromise between acceleration capability, more generally referred to as drivability, and energy usage or fuel consumption. This is, of course, the case for all vehicles, irrespective of their power source. Hence, two further sets of results to highlight the sensitivity of the gear ratio selection are shown in in Figs. 11 and 12, respectively.

In Fig. 11, the vehicle is assumed to start from rest and accelerate at a constant value of 0.7 m/s^2 up to its maximum speed. In Fig. 12, the vehicle effectively does the same thing except that it also now includes a period of constant running at each increment of 2.5 m/s. At first sight the values for selected gear ratio are not as smooth as might be expected as the speed changes but this is simply a result of the interpolation required on the motor torque/speed/efficiency map.

However, two important trends are highlighted; firstly, when accelerating, the selected gear ratio is nearly always around one or higher at the lower speeds, and secondly, for the vast majority of the constant speed conditions the gear ratio is around the 0.5 figure. The implication is that for the NEDC cycle, a simple transmission which just has two ratios may offer a combination of mechanical simplicity and significant energy improvement.

This idea is then tested by plotting out a probability distribution for the gear ratios selected by the continuously variable gearbox strategy during the NEDC cycle (Fig. 13). Each bar in in Fig. 13 represents a bandwidth of 0.4 of the gear ratio distribution. These results suggest that a gearbox based on just two ratios of around 0.6 and 1 may offer benefits.

4.1.3. Four speed gearbox

First however, the results are repeated assuming a rather conventional four speed gearbox with ratios of 0.5, 0.8, 1 and 1.5 is fitted. Again, it can be seen in Fig. 14 that this results that motor operation points fairly well clustered around the optimum motor efficiency region.

The overall energy consumption results over the total NEDC cycle are compared with those for the continuously variable gearbox in the top row of Table 6. The improvements over the no gearbox case are 18.7% for the CVT and 11.4% for the four speed gearbox. These are clearly very significant improvements, even allowing for the mechanical efficiencies of the gearbox in practice.

4.1.4. Two speed gearbox

Next, the results are repeated for a two speed gearbox with ratios of 0.5 and 1. A very simple gear selection strategy is now used; for constant speed running the value of 0.5 is used and for all other conditions a value of 1 is selected.

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The results in Fig.15 suggest that this approach leads to results similar to those obtained for the four speed case. And the results in Table 6 confirm this observation; the overall improvement for the two speed case is 9.2% compared with the 11.2% figure obtained for the four speed case and 18.7% for the CVT.

4.2 Simulation results for the USA FTP-75 cycle

4.2.1. No gearbox

The USA FTP-75 driving cycle along with the required torque values for the vehicle data used in this study are shown in Fig. 16. Although this is similar in length to the NEDC cycle, a major difference is apparent, it involves hardly any constant speed running. The consequences of this are twofold; the improvement offered by the CVT remains substantial at 19.2%, but the improvements offered by the two and four speed gearbox cases are significantly less than for the NEDC conditions.

These differences are seen more clearly, for example, in Fig. 17 which plots the motor operation points with no gearbox. Because the required acceleration in the USA FTP-75 is continuously changing, the motor operation points are much more widely spread than those for the equivalent NEDC results in Fig. 9.

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4.2.2. CVT gearbox

The results using the CVT arrangement are shown in Fig. 18 and as before, it is clear how the simple optimisation strategy works in congregating the points around the optimum motor efficiency region.

Finally, in Fig. 19, the probability distribution of gear ratios for the USA FTP-75 is plotted using a similar scale to the previous one (Fig. 13) for the NEDC cycle. The spread of gear ratio usage throughout the cycle is shown to be significantly greater than that for the NEDC cycle.

Overall, these results highlight one of the concerns facing the industry involved in low carbon vehicle technology. Whilst it is perfectly reasonable form a scientific viewpoint to compare competing schemes over a standard driving cycle so the vehicle powertrains are subjected to exactly the same requirements, it is also a matter for debate as to what constitutes a reasonable and representative driving cycle. And a further complication is that the answer to this question is likely to be substantially different in different markets around the world. There are obvious difference between transportation systems and road infrastructures across the three major automotive markets in Europe, USA and Far East. And already it can be observed that different 'standard' driving cycles have been recognized in these markets.

4.3 Effect of driving cycle

The sensitivity of these results to different driving cycles is summarised in Table 6 using those cycles which are available in the QSS software. The results are rather variable: the CVT arrangement nearly always results in significant improvements but the results for the two and four speed cases are not as promising.

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The results highlight a major issue which is relevant to all the work on comparisons of alternative propulsion systems. The energy usage results are highly sensitive to the driving cycle used. This conclusion emphasises the need for extreme caution in interpreting claimed improvements with competing systems for energy efficient vehicles.

For the results calculated here, the NEDC and USA FTP-75 cycles are probably the two most representative cycles involving a combination of city and urban driving over a substantial period. The Europe City and USA City are actually subsets of these cycles and the Japanese cycles are very short and simple.

4.4 Comparison of the results from two motors

The results of energy consumption for the vehicle with a generic motor are shown in Table 3. The results of energy consumption for the vehicle with a practical motor are shown in Table 6. The next stage is to analyze the difference between the two motors. Figure 20 shows the energy consumption for the two motors over 6 driving cycles. The vehicle with the practical motor has higher energy consumption than the vehicle with the practical motor. This is simply because some of the vehicle parameters are different (Tables 1 and 4). But the trends over driving cycles are the same; USA City I is the highest and Europe City is the lowest.

It is obvious that, for both the generic motor and the practical motor, the vehicle with a CVT has higher improvement than the vehicle with a 4 speed gear box, which is shown in Figs. 21 and 22. This is because with a CVT, more freedom of selecting the highest efficiency operation point is available.

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The average improvement over 6 driving cycles for vehicles with different combination of a transmission and a motor is shown in Table 7. The average improvement of for vehicles with the two motors ranges from 6.7% to 14.3%.

Figure 23 shows the improvement with a 4 speed gearbox with different motors. From this it can be seen that the vehicle with the practical motor over the Japan 10 mode has the lowest improvement. This is because for the practical motor, at the areas where speed or torque is near zero, data for the motor efficiency are not available. In these areas, the efficiency is all set to be 0.5. For some operation points where the required power (speed times torque) is too low, it is possible that along the constant power line, all 4 operation points with the 4 gear ratios falls into that area. So there is no improvement as a result of moving the operation points. Among the 6 driving cycles, the Japan 10 mode has the lowest maximum constant speed (40km/h). All of its constant speed points fall into the constant efficiency area, as shown in Fig. 24. This leads to the result that the vehicle with the practical motor and a 4 speed gearbox has the lowest improvement over the Japan 10 mode cycle.

Figure 25 shows the improvement with a CVT over the fixed single gear ratio case. In this case, there is a slight trend to suggest that the practical motor offers greater advantages compared with the generic motor assumptions.

5. Effect of drivability

The consumer acceptance of alternative powertrains depends on much more than just the headline economy figure and society's reaction to the feeling of contributing to the green economy. Vehicles still need to be pleasurable, convenient and satisfying to drive. Many of these aspects of driving dynamics are captured under the title of 'drivability'. Attempts have been made to quantify aspects of drivability and to a limited extent this has proved possible by defining new metrics. However, the interesting but elusive feature of drivability is that much of the assessment is based on qualitative judgements and the subjective impressions of the driver.

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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 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. The future work could focus the drivability of electric vehicles with different transmissions.

Some of the aspects used to assess drivability include; 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.

6. Conclusions

There are several promising outcomes form this work listed below; these must be interpreted in the context of the modeling approach used. The analysis is kept at a simple level in order to gain an initial understanding of whether the introduction of a geared transmission into an electric drivetrain offers any potential.

1. For the vehicle with a generic motor, 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.
2. 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.
3. For the vehicle with a practical motor, the use of a continuously variable gearbox in an electric drivetrain offers substantial improvements over the conventional arrangement of a single reduction gear; over the NEDC and USA FTP-75 cycles the improvements are 18.7% and 19.2 % respectively.
4. Using a simple two speed gearbox offers a worthwhile performance improvement of around 9.2% over the NEDC cycle, but a much smaller gain with the USA FTP-75 cycle which involves much less constant speed running.
5. 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.

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6. 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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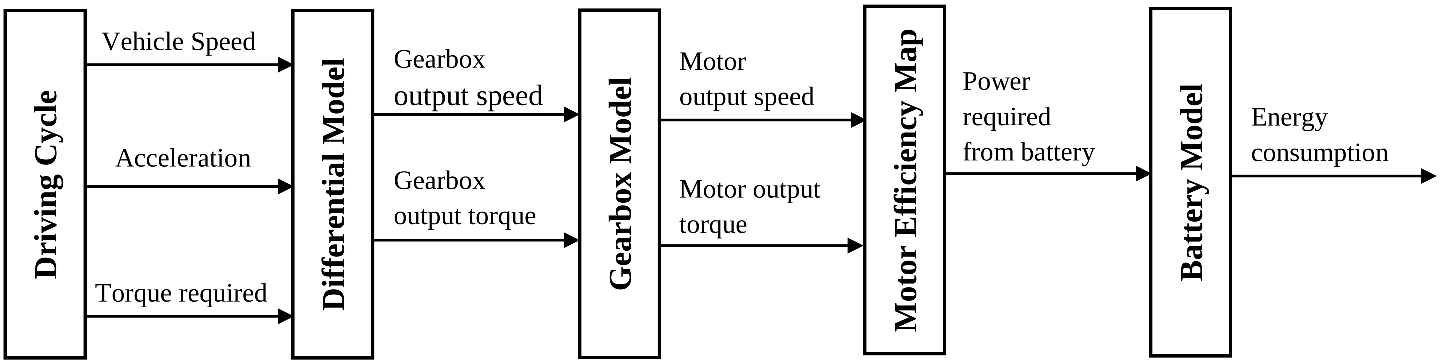

Figure 1. Block diagram of EV model

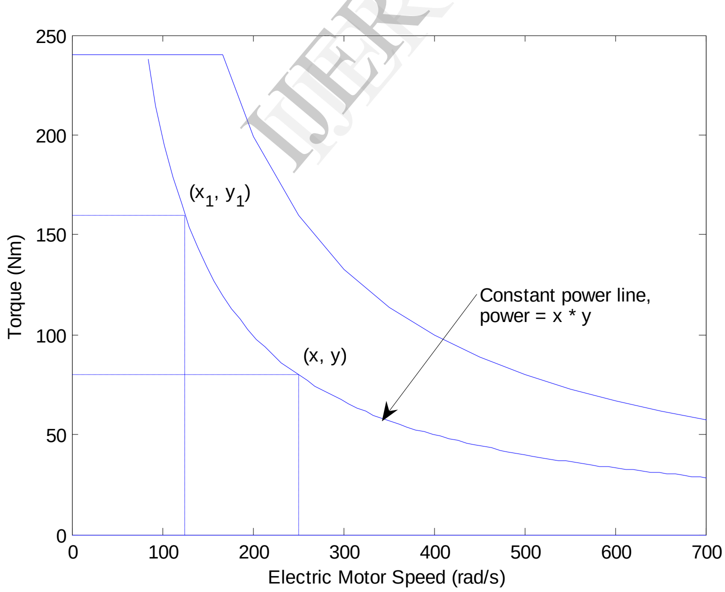

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Figure 2. Schematic diagram of selecting motor operation point

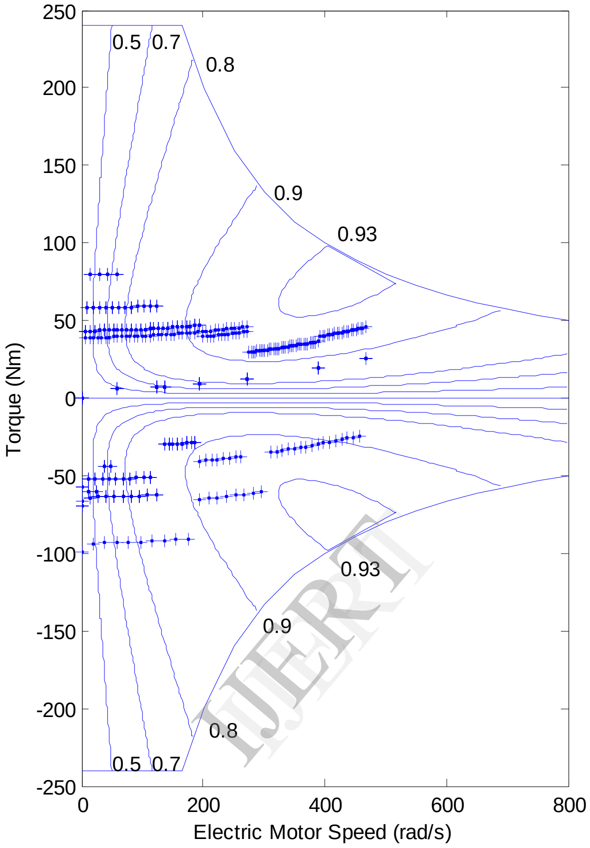

Figure 3. Motor operation points with no gearbox

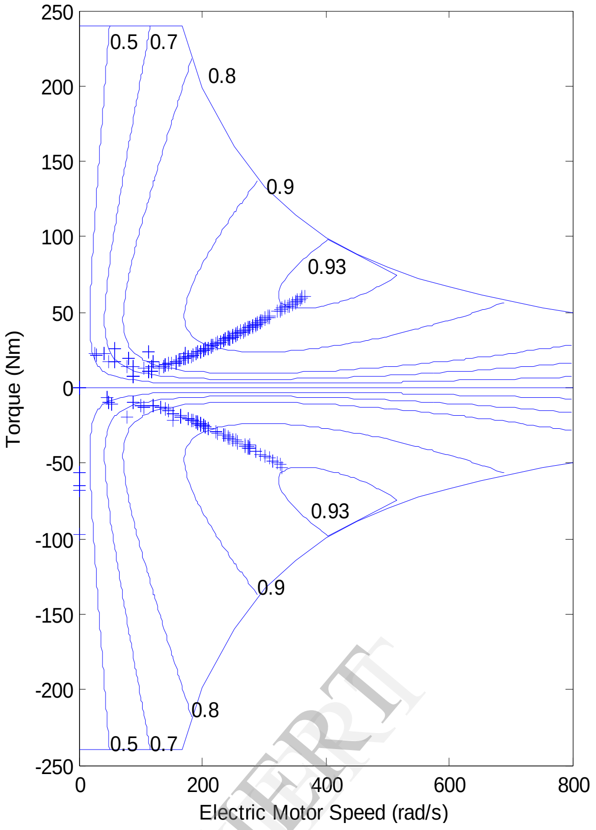

Figure 4. Motor operation points with continuously variable gear

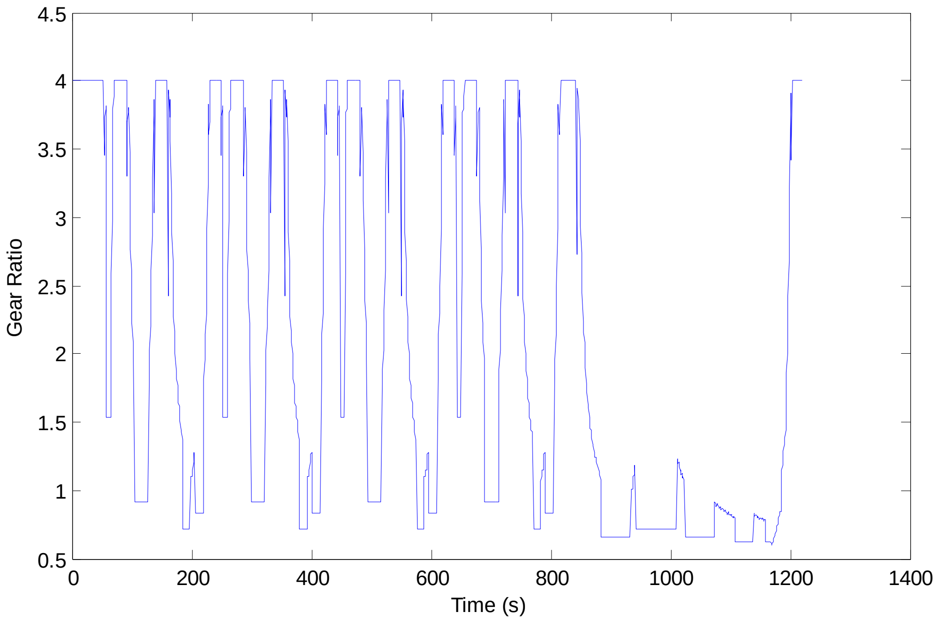

Figure 5. Gear ratios selected by optimisation strategy

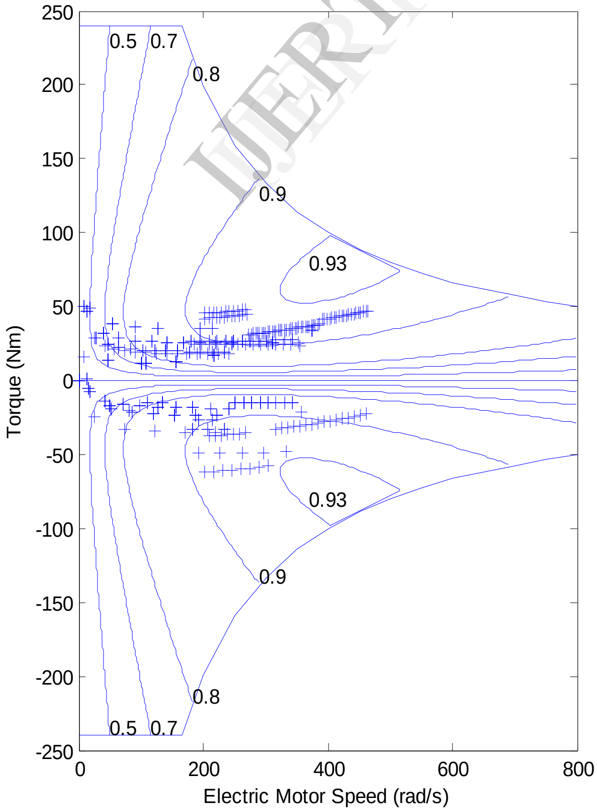

Figure 6. Motor operation points with four gear ratios

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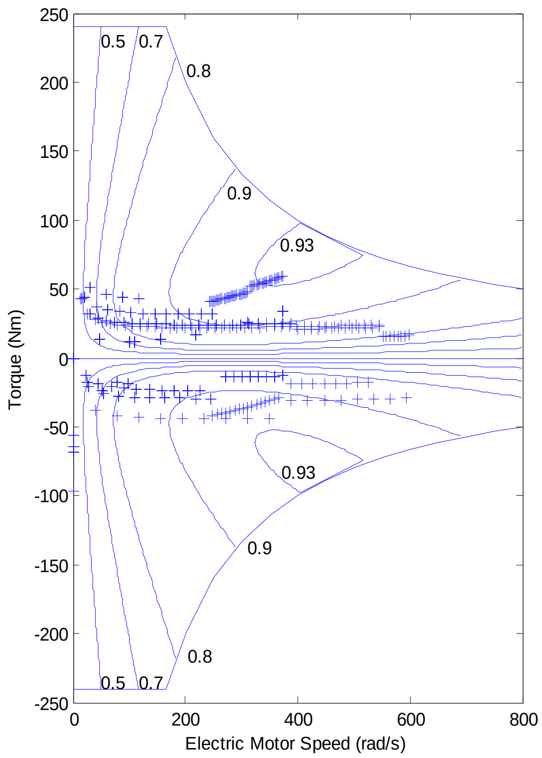

Figure 7. Motor operation points with two gear ratios

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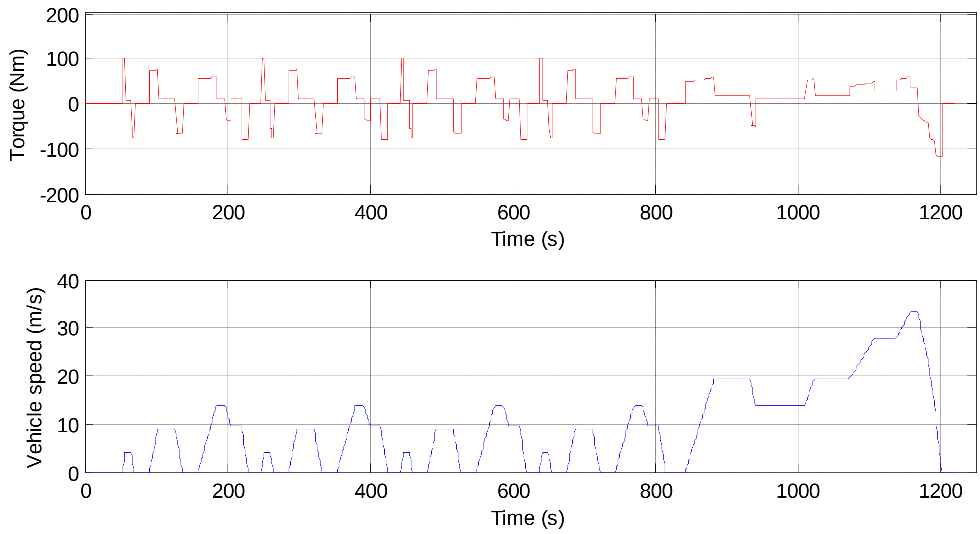

Figure 8. NEDC cycle – vehicle speed profile and required torque at the differential

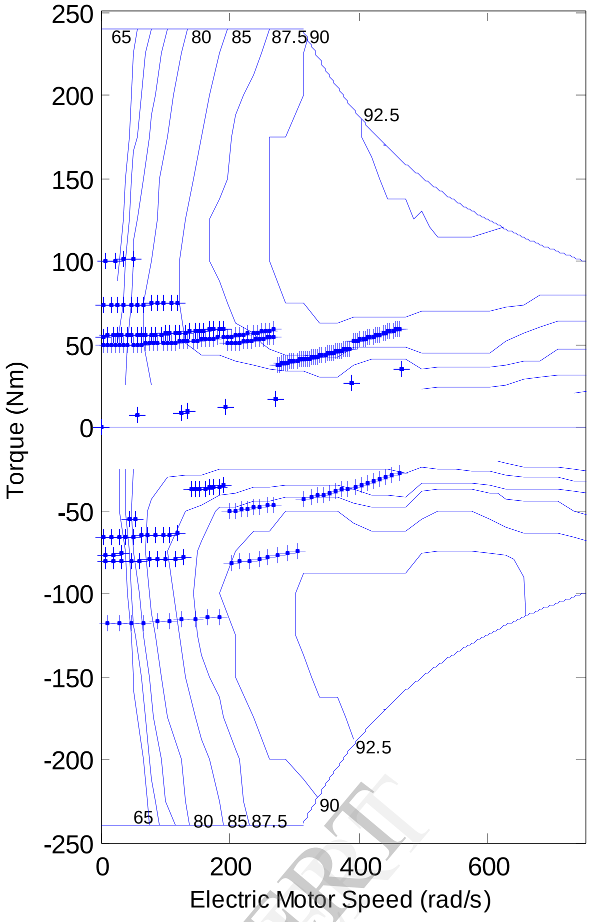

Figure 9. Motor operation points with no gearbox – NEDC cycle

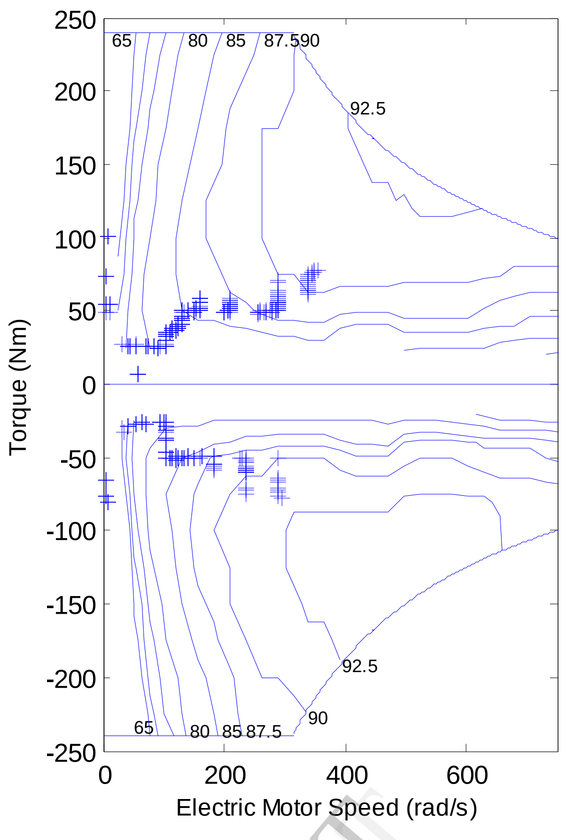

Figure 10. Motor operation points with a continuously variable gearbox – NEDC cycle

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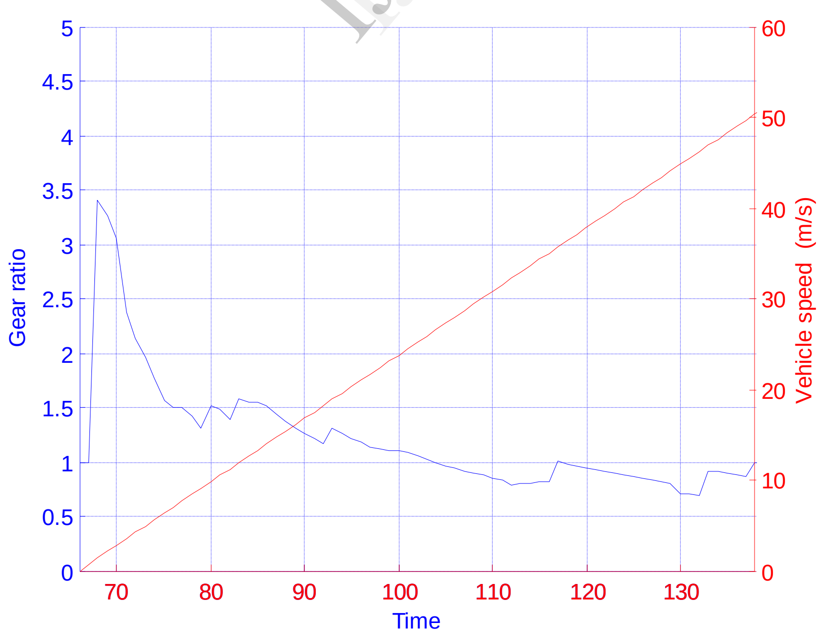

Figure 11. Gear ratio selection for maximum motor efficiency for a constant acceleration of 0.7 m/s^2

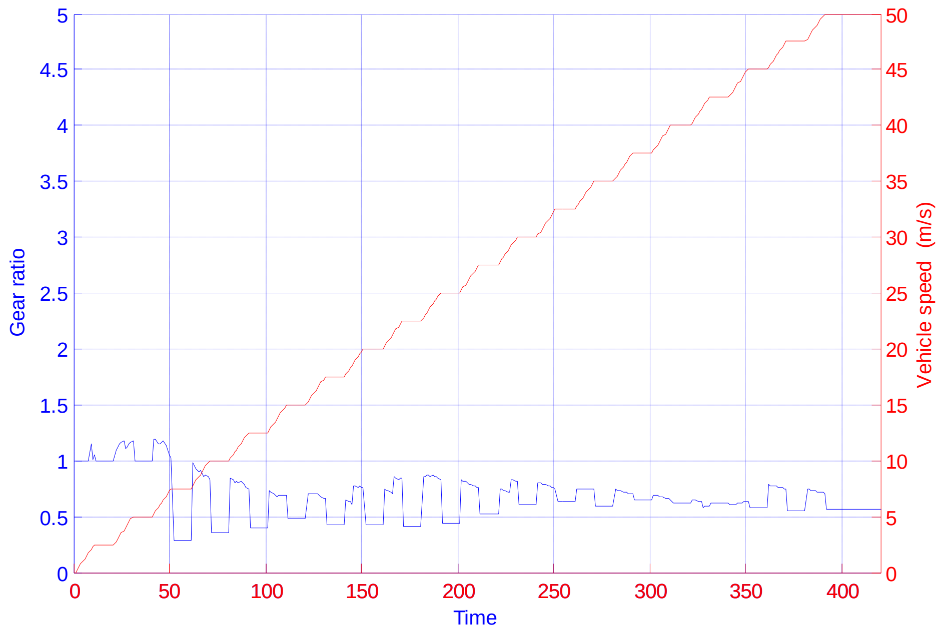

Figure 12. Gear ratio selection for maximum motor efficiency for increasing values of constant running speed

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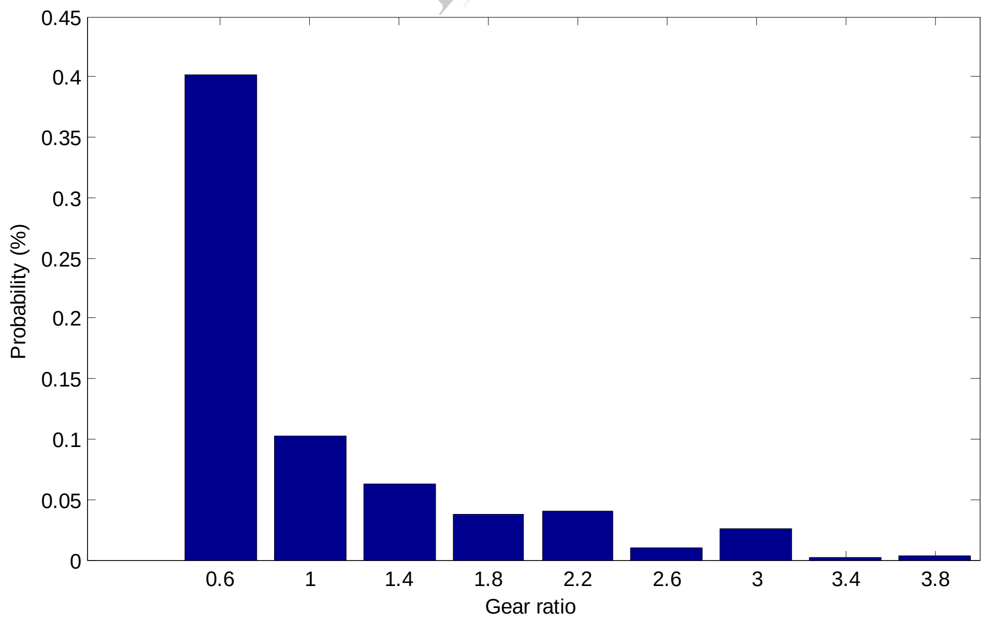

Figure 13. Gear ratio selection shown as a probability distribution over the NEDC cycle assuming a continuously variable gearbox

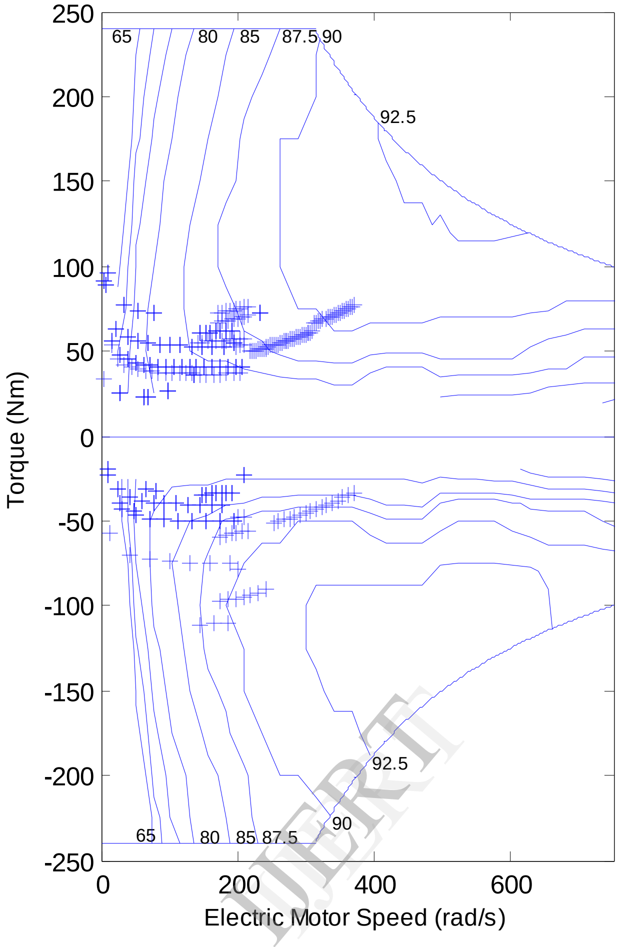

Figure 14. Motor operation points with a 4 speed gearbox – NEDC cycle

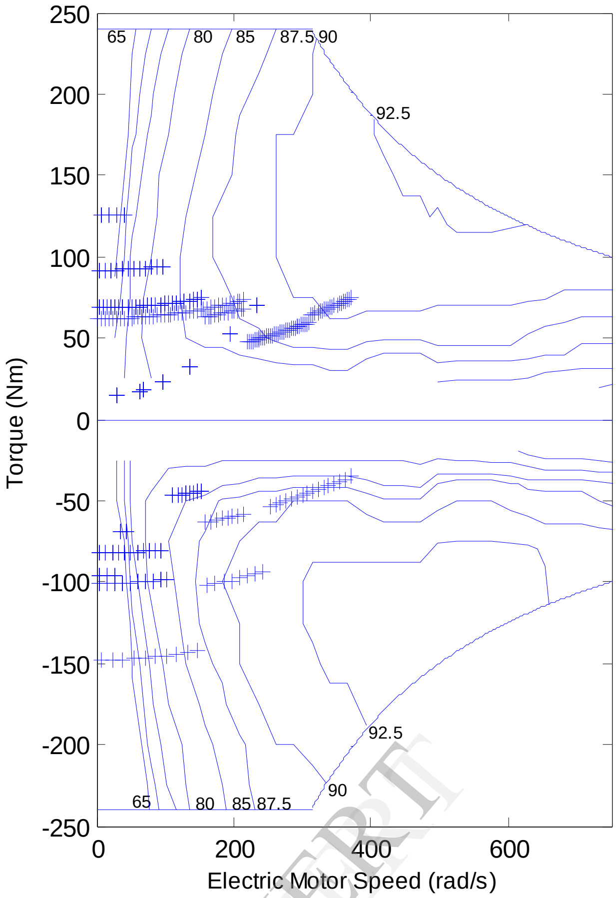

Figure 15. Motor operation points with a 2 speed gearbox – NEDC cycle

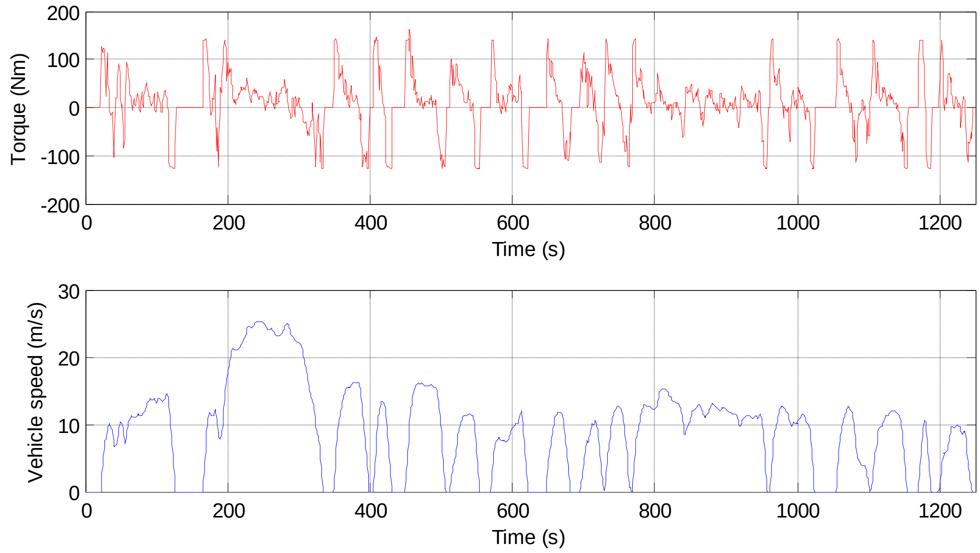

Figure 16. USA FTP-75 cycle – vehicle speed profile and required torque at the differential

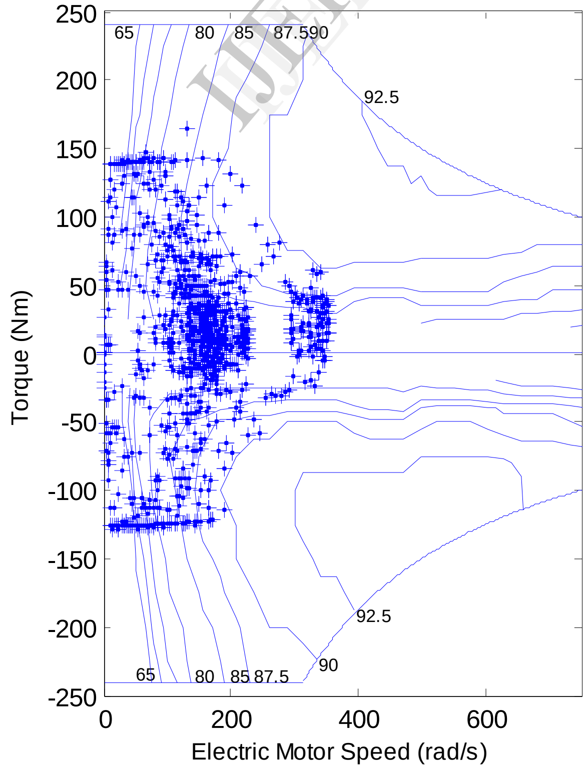

Figure 17. Motor operation points with no gearbox – USA FTP-75 cycle

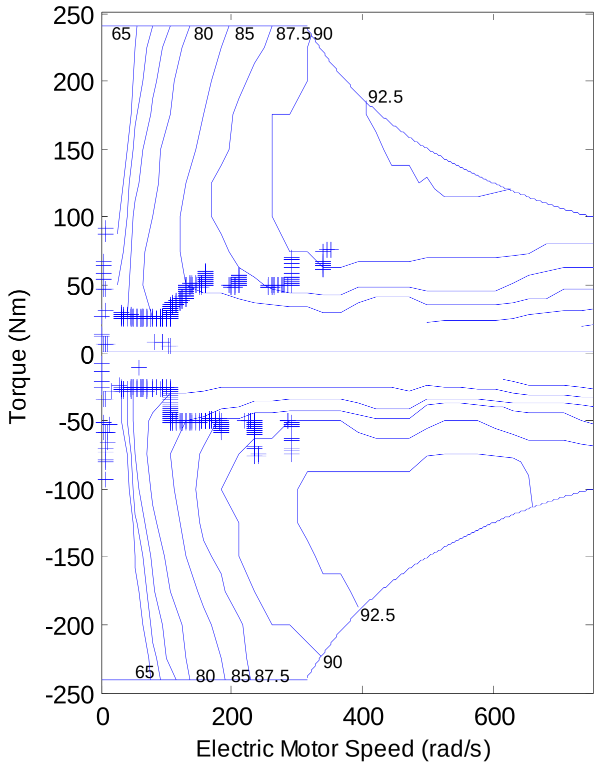

Figure 18. Motor operation points with a CVT – USA FTP-75 cycle

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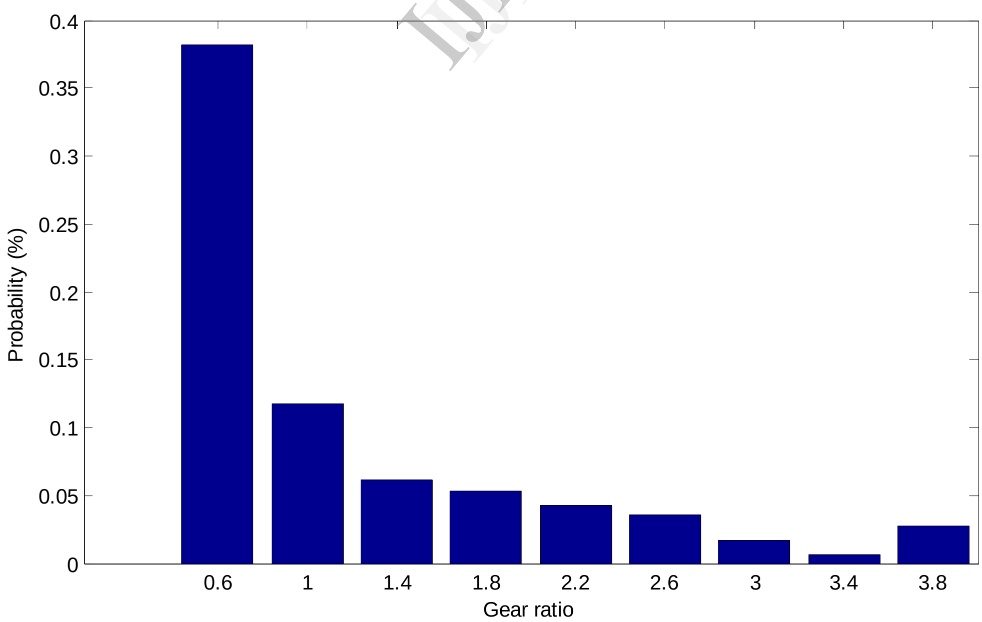

Figure 19. Gear ratio selection shown as a probability distribution over the USA FTP75 cycle assuming a continuously variable gearbox

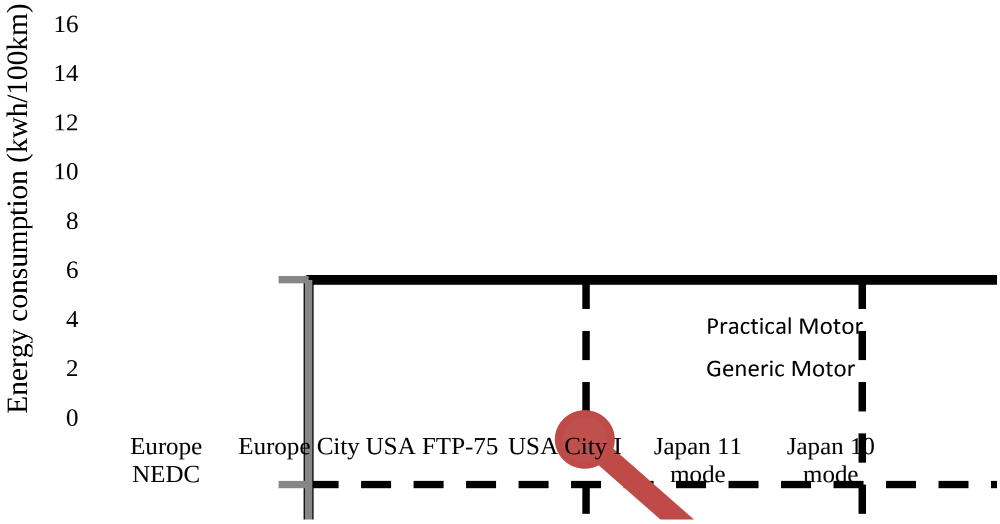

Figure 20. Comparison of energy consumption (No Gear)

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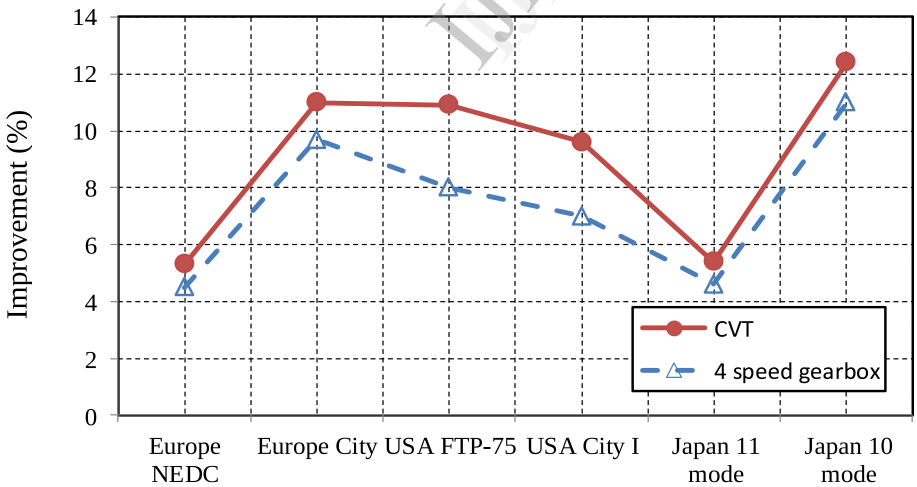

Figure 21. Comparison of the generic motor with a CVT and a 4 speed gearbox (Generic Motor)

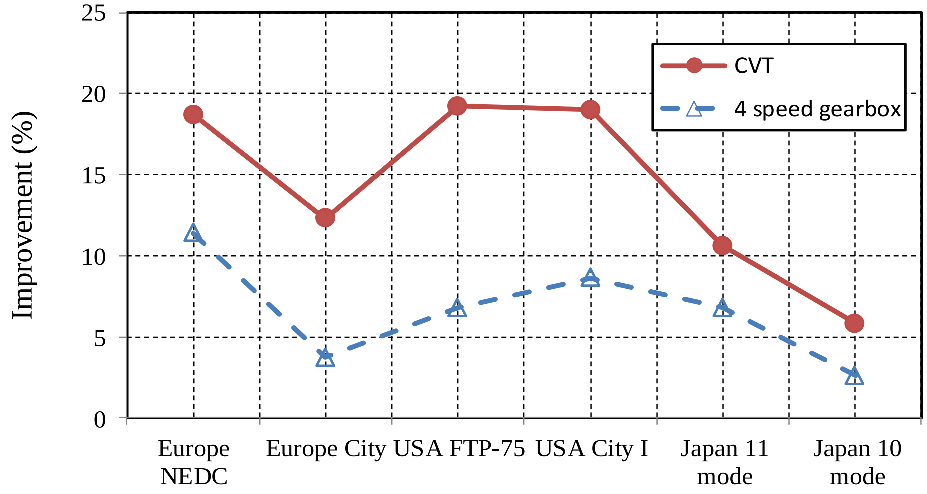

Figure 22. Comparison of the practical motor with a CVT and a 4 speed gearbox (Practical motor)

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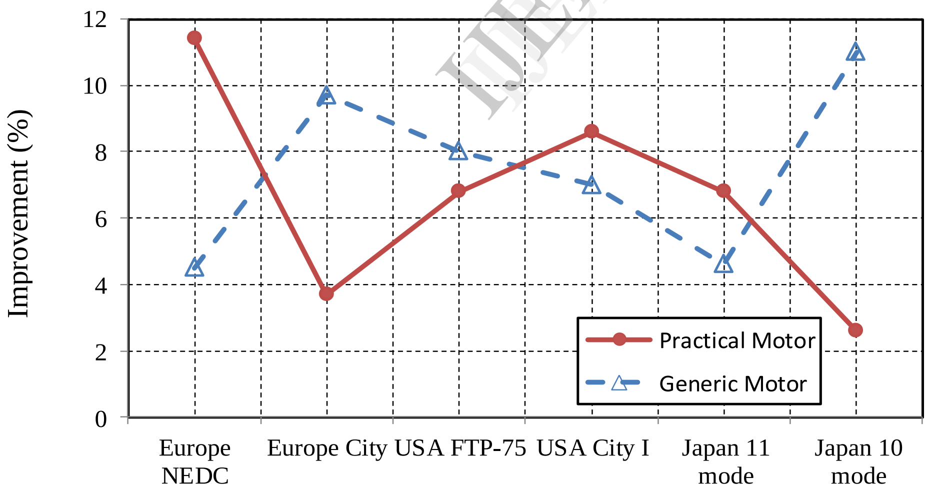

Figure 23. Improvement with a 4 speed gearbox

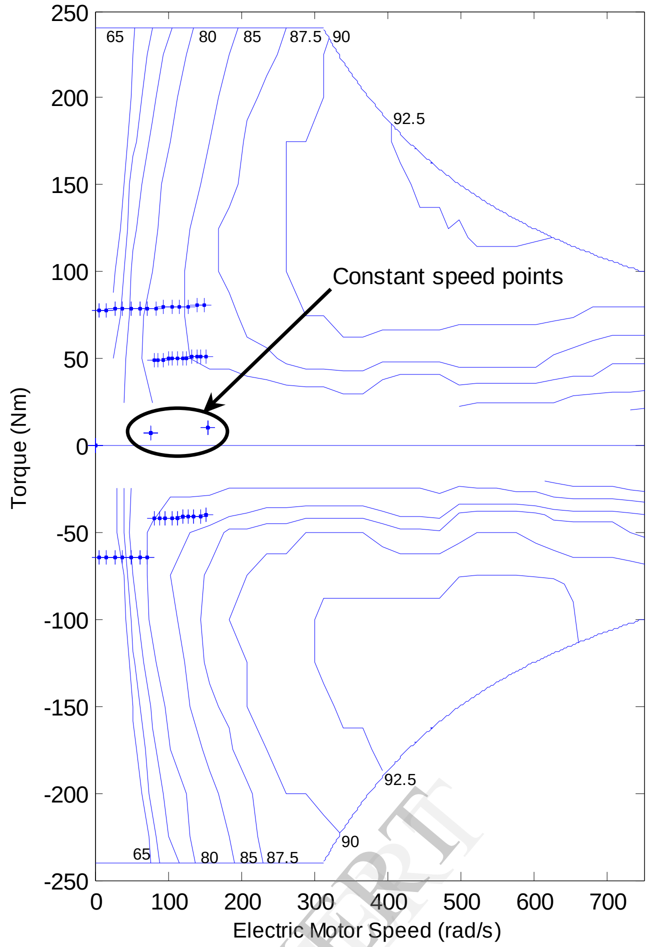

Figure 24. Motor operation points with no gearbox – Japan 10 mode

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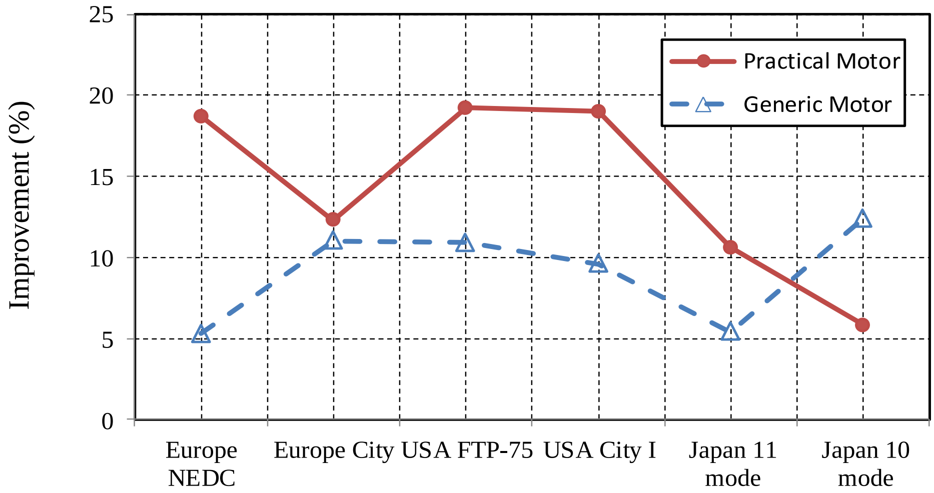

Figure 25. Improvement with a CVT

Tables

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

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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

Table 3. Comparisons of improvements in energy consumption over 6 different driving cycles (generic motor)

Driving cycle	No gearbox	4 speed gearbox		Continuously variable gearbox	
	Energy consumption (kWh/100km)	Energy consumption (kWh/100km)	Improvement %	Energy consumption (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

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Table 4. Vehicle parameter data for the model with UQM motor

Parameter, units	Value
Total vehicle mass, kg	1200
Wheel diameter, m	0.5
Aerodynamic drag coefficient	0.3
Frontal area, m^2	2
Rolling resistance coefficient	0.008
Motor maximum torque, Nm	240
Motor maximum speed, rad/s	750
Motor power – continuous , kW	45
Motor power – maximum, kW	75

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Table 5. Energy consumption over the NEDC cycle for different final drive ratios

Final drive ratio	Energy consumption per 100km (kWh/100km)
3	14.26
3.5	14.43
4	15.60
5	16.11

Table 6. Comparisons of improvements in energy consumption over 6 different driving cycles (practical motor)

Driving cycle	**No gearbox**	**Continuously variable gearbox**		**4 speed gearbox**		**2 speed gearbox (no acc: 0.5; acc: 1)**	
	Energy consumption (kWh/100km)	Energy consumption (kWh/100km)	Improvement %	Energy consumption (kWh/100km)	Improvement %	Energy consumption (kWh/100km)	Improvement %
Europe NEDC	14.4	11.7	18.7	12.8	11.4	13.1	9.2
Europe City	9.7	8.5	12.3	9.3	3.7	9.7	0
USA FTP-75	13.2	10.7	19.2	12.3	6.8	12.6	4.1
USA City I	14.8	12.0	19.0	13.6	8.6	14.0	5.7
Japan 11 mode	10.4	9.3	10.6	9.7	6.8	9.9	5.4
Japan 10 mode	9.4	8.8	5.8	9.1	2.6	9.4	0

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Table 7. The average improvement over 6 cycles

	CVT	4 speed gearbox
Generic motor	9.1%	7.5%
Practical motor	14.3%	6.7%