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GEAR RATIO OPTIMIZATION OF SINGLE AND TWO-SPEED TRANSMISSION FOR AN ELECTRIC MOTORCYCLE

Jolana Heřmanová

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Automotive, Combustion Engine and Railway Engineering, Technická 4, 166 07 Prague 6 – Dejvice, Czech Republic

correspondence: jolana.hermanova@fs.cvut.cz

Abstract. Most electric vehicles have a single-speed transmission as the traction characteristic of an electric motor allows operation with sufficient motor torque at low and high speeds. Then, the selection of the single-gear ratio is a trade-off between available torque for acceleration (or gradability) at lower speeds and the designed maximum vehicle speed corresponding to the electric motor's maximum speed limit. Nevertheless, the multiple-speed transmission can be used, and the vehicle can benefit from improved acceleration at low speeds and higher maximum speeds. In this paper, the gear ratio of a single-speed transmission for an electric racing motorcycle is optimized to achieve a trade-off between acceleration, lap time, and maximum speed. With the same goal, the gear ratios for two-speed transmission are optimized, and the results are compared.

Keywords: Gear ratio optimization, battery electric vehicle, racing motorcycle.

1. Introduction

As the traction characteristic of the electric motor is usually sufficient to propel the vehicle, most BEVs have a single-speed transmission. There are some exceptions, and the reason for using a two-speed transmission instead of a single-speed transmission has always been the same. It is to achieve sufficient maximum vehicle speed and provide good vehicle acceleration (or gradability). Another way, other than using additional gear, to get better acceleration times is to use a more powerful and more expensive motor.

Figure 1 shows typical electric motor characteristics. The main visible features are these:

- high available torque at low motor speed, goes roughly to zero speed with constant torque (the color is hidden for efficiency under 50 %),
- very low efficiency in high load and low speed (top left corner), under 50 %,
- area of constant motor power and decreasing torque, approximately (in this specific case) for motor speed above 4000 RPM,
- the area of best efficiency is located in higher speed and moderate loads, with maximum efficiency of up to 97 %,

The gear ratio has to be chosen with respect to a motor speed range and vehicle required speed range, and on the other hand, with respect to demanded torque on wheels ensuring sufficient acceleration. The gear ratio then works as a multiplier for torque and a divisor for speed, as shown in Figure 2. The figure shows the traction characteristics in a wheel torque equivalent; the first gear (higher gear ratio) of a two-speed transmission multiplies the torque and shortens the speed range, whereas the second gear allows a higher speed range but lower torque.

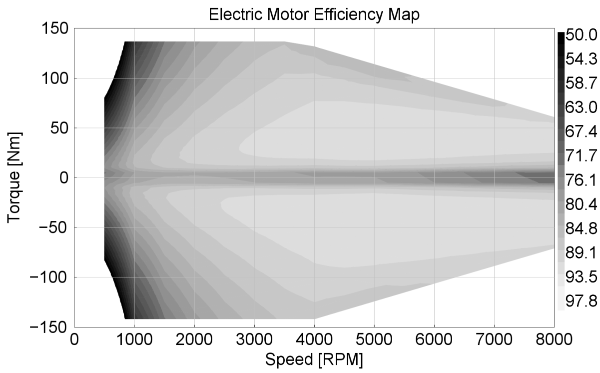

Figure 1. Electric motor efficiency map example.

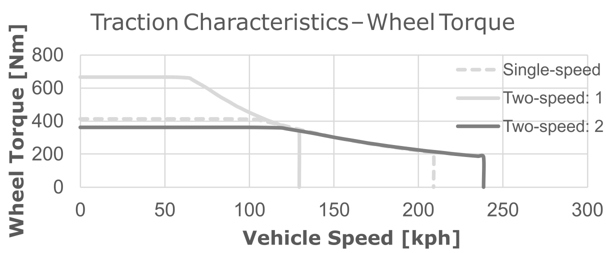

Figure 2. Traction characteristics.

Thus, these conflicting aspects must be considered for the correct gear ratio design.

Most of the producers in the past used single-gear transmissions mainly due to the complexity of the two-speed transmissions. Among these examples in recent decades is the first Tesla Roadster. It was planned to have two-speed transmission (with gear ratios – GR of 14.3 and 7.4 [1, 2]), but due to higher complexity, the Roadster was later produced with a single-speed transmission (GR 8.27) [3]. Nowadays,

Single-speed transmission	Two-speed transmission
a trade-off between acceleration and maximum speed	allows higher maximum vehicle speed,
lower complexity	allows higher vehicle acceleration
lower weight (simpler gearing)	electric motor can be used in areas with higher motor efficiency
lower efficiency losses in gearing	can use a smaller (less powerful) motor, reduced mass and price, and increased efficiency

TABLE 1. Single-speed and Two-speed transmission advantages and disadvantages.

another BEV that uses the two-speed transmission is a Porsche Taycan (GR around 15 and 8 at the rear, 8 at the front [4]) and Audi RS E-tron GT (GR 15.56 and 8.16 [5]). Taycan predominantly uses the second gear. The first gear is used in sport mode and at low speeds. The gearbox weighs approximately 70 kg and uses an electronic limited-slip differential. For transition between the two gear sets, there is a single actuator [6]. The shift to the second speed occurs when reaching roughly 75 kph [7].

Another BEV using a two-speed transmission is, for example, Rimac Concept One, which has four motors in total, one for each wheel (located in axle), and with single-speed transmissions at the front and two-speed double-clutch transmission at the rear. For Concept-Two, they wanted to eliminate the two-speed transmission because of complexity and weight; still, because of demands on better performance (0–100 kph acceleration), they firstly were forced to use the two-speed transmission again. Finally, a year later, they presented a car with a single-speed transmission. They achieved it with an electric motor (EM) and inverter redesign, which allowed them to use the EM at a maximum of 17 700 RPM [8, 9]. BMW i8 PHEV is equipped with a two-speed transmission (developed by GKN) for the electric motor at the front axle [10, 11]. ZF also presents its two-speed transmission design with the electric motor [12, 13]. Jeep Magneto might have a multiple-speed gearbox because of off-road functionalities. Also, EV trucks, especially heavy-duty ones, will likely be equipped with multi-speed transmissions because of the high torque at low speeds and efficiency at high speeds. Other transmissions are being considered (like CVT) or usage of multiple motors [14].

The main problem with a two-speed transmission is that it must be robust enough to deal with the high torque of the electric motor; there are reliability problems and requirements for more maintenance. It economically makes sense in vehicles with higher battery capacity and in higher performance systems [15].

Overall, manual multi-speed motorcycle gearboxes are not very frequent in the market. These are just a few examples. Brammo Empulse R (production versions available around 2012) was produced with a clutch and six-speed transmission. It benefited over its competitor Zero S in a launch and quicker acceleration. Otherwise, a manual transmission lowers the comfort and lacks the smoothness of single-speed competitors [16, 17]. A Chinese manufacturer, QJ-Motor, announced a new model, QJ7000D, in 2021, featuring manual transmission, but it still has not reached production [18]. It is possible to find limited information about a prototype with a two-stage SmeshGear Transmission [19]. Also, an Indian producer, Matter, promises a motorcycle with a four-speed manual transmission (Matter Aera 5000) [20]. Lastly, Kawasaki announced in 2020 a motorcycle with a four-speed manual transmission [21]. A different approach was taken by Kymco. The announced SuperNex and RevoNex promise a simulated six-speed transmission. Production-ready variants are still expected [22, 23].

A comparison of fundamental properties of single-speed and two-speed transmission is shown in Table 1.

1.1. Two-speed transmission in the research area

According to studies [24], using two-speed transmission can bring a 4–5 % increase in energy efficiency. In [25], the authors compared a small experimental vehicle with a single-speed transmission and gear ratio of 10 versus the same vehicle with a two-speed transmission with gear ratios of 14 and 10. The results were 3.4 % savings in energy consumption (during a specific testing scenario).

Transmissions usually used in BEVs are mostly simplified DCTs; another configuration can be based on double-row planetary gears or single planetary gear (with friction brake and shift clutch). AMTs consist of two gear pairs with synchronizers, shift forks, and actuator motors. The power interruption can also be filled by a motor on the second axle. Many other transmission layouts primarily aim to diminish the power interruption during gearshifts and, thus, try to achieve a seamless gear shift. In general, the main problems of two-speed transmissions are gear ratio design and shift schedule definition, then the power interruption, improvement of the shift quality, reduction of the jerk, and reduction of power loss [24–27].

According to the [24], the multiple-speed transmissions are likely to spread in sports and luxury cars first, then in logistics vehicles, and potentially in ordinary vehicles.

1.2. The goal of the article

This article aims to design, optimize, and compare two transmission variants for an electric racing motorcycle. The 1D simulation models of the motorcycle with single-speed and two-speed transmission were built, the gear ratios were optimized in specific scenarios, and then the results were compared.

The scenarios are derived from the requirements of the MotoStudent competition to reflect the points awarded in the competition as much as possible [28].

Then, the vehicle performance was assessed for two different electric motor settings: Limited Torque variant and Maximum Torque variant. This reflects the real demands of the motorcycle and its components' usage. The setting of maximum torque that the electric motor can deliver varies greatly, mainly depending on the performance of the motor controller, motor cooling system, and other systems.

The factors, objectives, and other factors had to be defined to perform the optimization.

2. Methodology

The simulation model and the simulated vehicle are described, followed by the main component parameters, the scenarios, and the description of the optimization process.

2.1. Simulation model

The simulation model was built in GT-Suite 1D simulation software (see Figure 3). The model consists of compounds that represent the main components of the vehicle: the vehicle chassis (with its retarding forces), the transmission, the electric motor and battery, the battery controller, and the driver. Each component contains its main parameters (vehicle parameters are shown in Table 2).

The additional mass for the two-speed transmission was not considered because the baseline motorcycle is already equipped with a transmission that transfers the motor power mounted in a rotated position. The transmission consists mainly of two bevel gears, a case, and oil filling. The overall mass of the two-speed transmission was expected to be similar.

The model is controlled in a dynamic mode with a PID controller inside the driver compound. It is designed to follow the required speed (the drive cycle is shown in Figure 4); in this case, the desired speed is input in the form of a maximum speed limit (distance dependent) that the vehicle could virtually ride with respect to corners. One of the model's limitations is that it simulates the ride straight. Thus, the corners must be processed for the given track in advance. The change in wheel diameter in corners is neglected; this could be solved in future model development. Figure 4 shows what the drive cycle looks like. As said, it shows the maximum speed limit depending on the distance driven. As a PID regulator controls the model and takes into account all physical limits, the vehicle accelerates as much as possible in areas of high-speed limit, then brakes before the limited speed area and accelerates again. The value of 300 kph was chosen as a speed that is high enough not to be reached by this specific motorcycle to achieve a full throttle demand during all these sections. As the start of the race is straight, the cycle begins with this maximum speed/maximum power demand. The motorcycle's actual maximum speed and also the simulated speed through the cycle are visible, for example, in Figure 5.

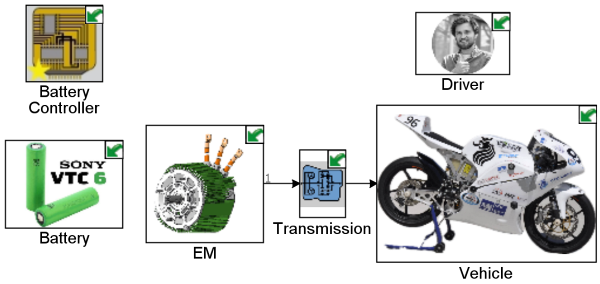

Figure 3. Simulation model.

Base vehicle mass	166 kg
Frontal area	0.407 m^2
Drag coefficient	0.55
Tire rolling resistance factor	0.015
Tire rolling radius	300.5 mm
Driver mass	80 kg

Table 2. Vehicle parameters.

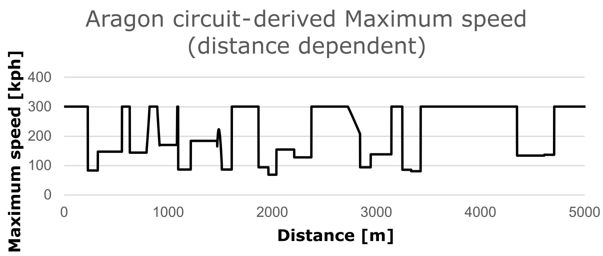

Figure 4. Aragon drive cycle.

The gearbox is modeled by a simple compound containing gear ratio, gear efficiency, and moment of inertia. In the case of a two-speed transmission, the gearshift takes 0.2 s.

2.2. Electric motor controller setting

Figure 6 shows the chosen electric motor controller settings implemented into the vehicle model. The maximum torque line represents the maximum torque that the motor is able to deliver according to the manufacturer's datasheet. It represents the upper limit of what the motorcycle can deliver and what we wish to reach.

Nevertheless, in reality, it is not easy to reach the datasheet values. This is the reason why we also work with the limited torque variant. It represents what was possible to get from the motorcycle system in real conditions. The goal in future motorcycle development is

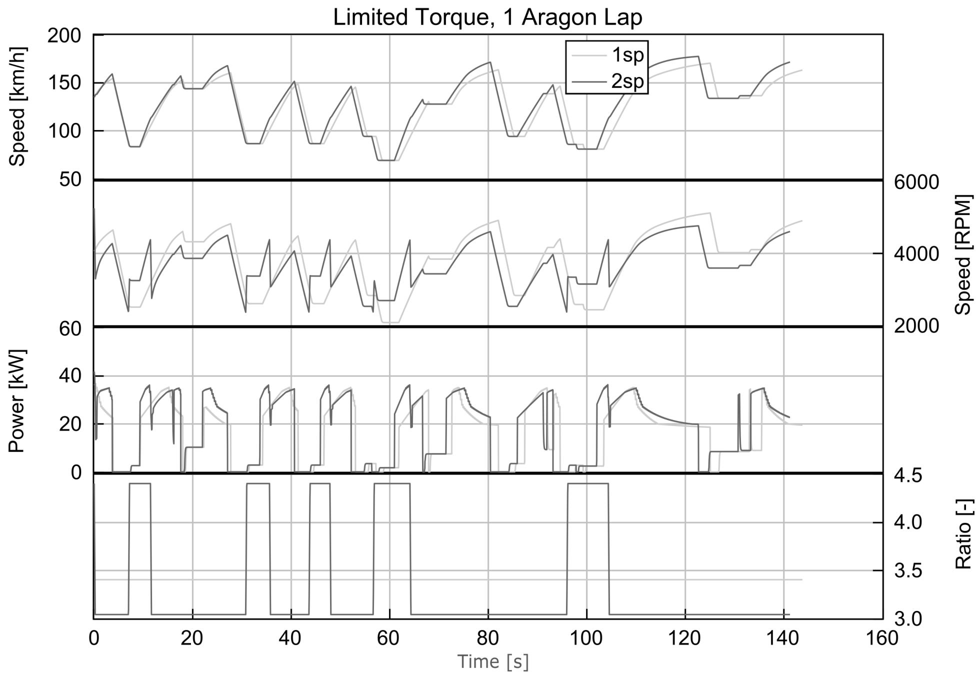

FIGURE 5. Results comparison – Limited Torque.

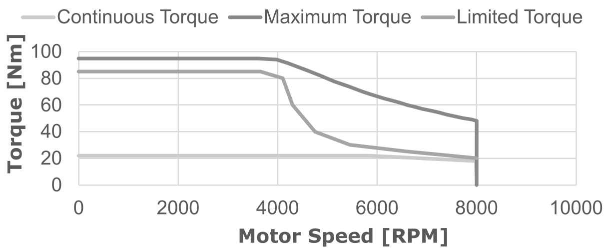

FIGURE 6. Motor controller settings.

Disciplines awarded by points	Points
Race at Aragon circuit	150
Fastest lap (quali and race)	40 + 30
Acceleration test (150 m)	80
Gymkhana	60
Maximum speed	30

TABLE 3. MotoStudent disciplines awarded by points.

to get as close as possible to the maximum curve. The gear ratio is thus optimized for both variants, with the expectation that the results will give a sufficient and interpolable background (if, in future development, the limited torque curve gets closer to the maximum curve). The work also represents a methodology that can be easily repeated with different inputs, like new motorcycle evolution, new electric motor, different battery cells, etc.

2.3. SCENARIOS

Before starting the optimization process, the precise goals and specific scenarios have to be defined.

The primary purpose of this motorcycle is to race and achieve the best possible results in the competition of many similar motorcycles. It is thus necessary to constantly push the limits further. In this case, the goals can be derived from the parameters of the MotoStudent competition. Table 3 shows the list of disciplines and maximum points awarded.

Position in the race at Aragon is a discipline very similar to the fastest lap (measured in qualification and during the race). Thus, the first chosen scenario is a one-lap race at the Aragon circuit as it captures both.

The Acceleration test and gymkhana have a low speed range in common. The crucial thing in the acceleration test is the available and transferable torque. On the other hand, the gear ratio should be chosen taking into account also the maximum vehicle speed at the finish line at the end of 150 m straight.

The gymkhana is focused on the motorcycle's maneuverability and acceleration. It consists of a ride between the cones with many cornering, acceleration, and braking sequences at a very low speed.

At this point, the assumption is made that the optimum gear ratio for the acceleration test will also function well in the gymkhana test. Also, the torque transferability from the rear wheel to the tarmac has to be taken into account; this adhesion limit makes it purposeless to increase the gear ratio above a certain limit. Thus, the second scenario is the 150 m acceleration test.

The maximum speed can be assessed with respect to the results from one lap of racing at Aragon. To some extent, the motorcycle's maximum speed has to be high enough to achieve a good lap time at the

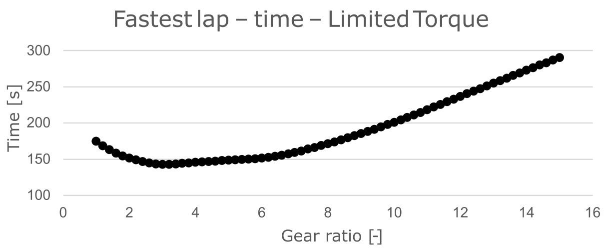

Figure 7. Results: single-speed transmission, limited torque, one lap Aragon.

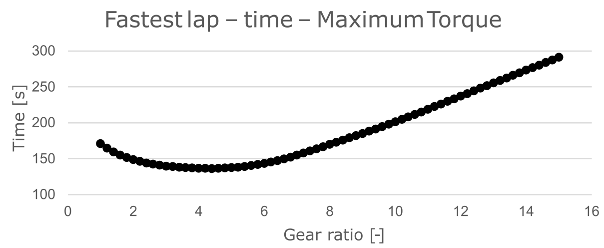

Figure 8. Results: single-speed transmission, maximum torque, one lap Aragon.

Aragon circuit; thus, these disciplines are related. The points awarded in the competition have little impact on the overall rating (30 points versus 150+40+30 for race and fastest lap disciplines), so the maximum speed is not a top priority.

2.4. Methodology of optimization

The single-speed transmission variant is much simpler to assess. A Design of Experiment (DOE) is sufficient to show the dependencies and approximate the optimum.

The situation is much more complex for the two-speed transmission. The factors in the optimization case are gear ratio 1, gear ratio 2, the motor speed to shift up to the second gear, and the motor speed to shift down to the first gear. The search algorithm used was Genetic Algorithms (GA).

The scenarios are assessed separately, as they place different demands on the motorcycle's performance. The maximum torque and limited torque variants are also evaluated.

3. Results

The results section is divided into several subsections. It starts with results for the single-speed variant – one lap scenario and acceleration scenario. The results for the two-speed transmission variant follow.

3.1. Single-speed transmission results

The results of the single-speed transmission variant were prepared as a DOE with changing the gear ratio in an interval from 1 to 15. The interval is wide enough to contain an area around the optimum and a sufficient number of designs on both sides.

	Limited Torque	Maximum Torque
GR1 [-]	3.4	3.9
Lap time [s]	142.0	136.0
Max speed [kph]	170.6	211.0

Table 4. Results: single-speed transmission.

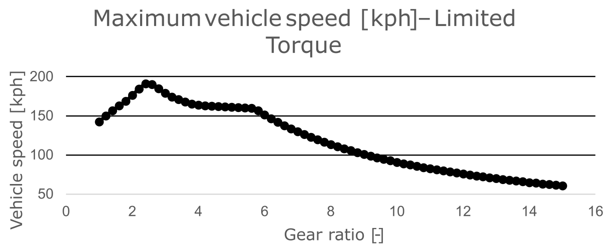

Figure 9. Results: single-speed transmission, limited torque, maximum speed.

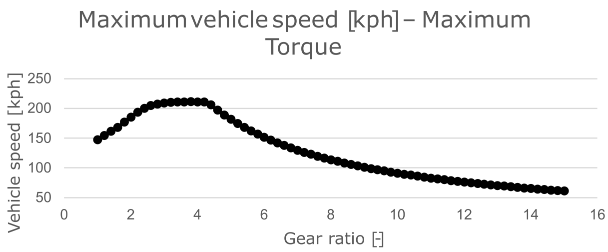

Figure 10. Results: single-speed transmission, maximum torque, maximum speed.

3.1.1. One Lap

The results for one racing lap for both torque limit variants are shown in Figures 7 and 8.

It is apparent from the figures that the optimum gear ratio lies in a wider interval. For the variant of limited torque, it is approximately from 2.6 to 4 with a lap time under 145 s, and for the maximum torque variant, it lies in the interval from 3.5 to 5.2 with a lap time under 138 s.

The minimum values are 142.0 s for GR of 3.4 for the limited torque variant and 136.0 s for GR of 3.9 for the maximum torque variant (see Table 4).

The maximum speeds achieved during the one-lap scenario are shown in Figures 9 and 10. The vehicle can reach a maximum speed of around 190 kph in the variant of limited torque. In contrast, the variant with maximum torque achieves 211 kph, and the maximum speed is achievable in a wider range of gear ratios (as the maximum motor power does not decrease with the higher motor speed in the case of the maximum torque variant and the motor torque follows thy hyperbola as shown in Figure 6).

3.1.2. Acceleration

The results for the acceleration scenario are shown in Figures 11 and 12. The limited torque variant achieves the minimum time of 7.6 s (on 150 m acceleration) for a gear ratio of 8.8. Still, it achieves a similar

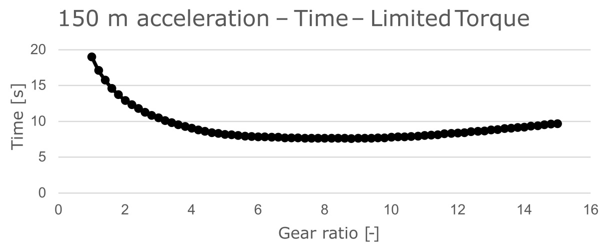

Figure 11. Results: single-speed transmission, limited torque, 150 m acceleration.

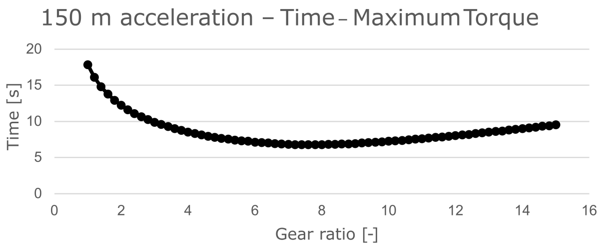

Figure 12. Results: single-speed transmission, maximum torque, 150 m acceleration.

result with a gear ratio of 7.4 to 9.4. In contrast, the maximum torque variant achieves the lowest values of 6.7 s for gear ratio 7.6, and results are similar for gear ratio from 7.2 to 8.

3.2. Two-speed transmission results

The results for the two-speed transmission variant were acquired by a Genetic Algorithm optimization. The algorithm calculated approximately 400 designs for each variant, and the results are firstly shown as interim results in figures as gear ratio to design and then in the table after choosing the best representative design. As was visible from the single-speed transmission results, it is impossible to choose one optimal point. Thus, the results should better be interpreted as intervals where the optimum is close. To easily compare, one design was selected from each variant to represent the results.

3.2.1. One Lap

The interim results for one Aragon lap scenario for the maximum torque variant are shown in Figure 13 as gear ratio to design number. The figure shows how the algorithm worked through the given space to the optimum values. The acceptable design for each torque variant was chosen from the simulated designs, summarized in Table 5.

The chosen design for the limited torque variant has a gear ratio of 4.4 for the first gear and 3.0 for the second gear. The gear is shifted when surpassing the motor speed of 4 367 RPMs; the downshift is done when the speed lowers under 2 360 RPMs. With these values, the vehicle achieved a lap time of 140 s and, at the longest straight, achieved a maximum speed of 177.7 kph.

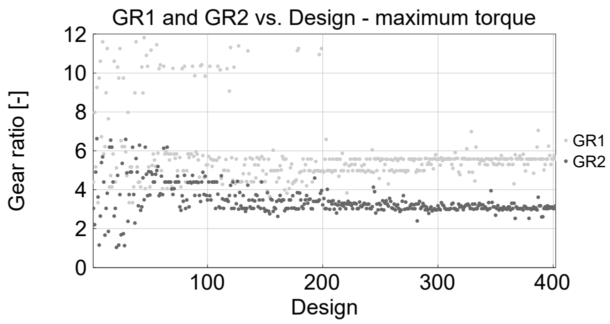

Figure 13. Interim results: two-speed transmission, maximum torque, one Aragon lap.

	Limited Torque	**Maximum Torque**
GR1 [-]	4.4	5.7
GR2 [-]	3.0	3.0
RPM_up	4 367	7 730
RPM_down	2 360	2 537
Lap time [s]	140.0	134.1
Max speed [kph]	177.7	211.5

Table 5. Results: two-speed transmission.

The chosen result for the maximum torque variant has a gear ratio of 5.7 for the first gear and 3.0 for the second gear. The upshift and downshift are then at 7 730 and 2 537 RPMs. The lap time achieved is 134.1 s, and a maximum speed of 211.5 kph.

3.2.2. Acceleration

As vehicle adhesion is limited, and the gearshift itself represents a short time delay, it is not beneficial to use the two-speed transmission for the acceleration test. Thus, the results for the single-speed transmission are applicable.

4. Discussion

The results for one Aragon lap scenario are summed up in Table 4 and 5.

The first point that should be mentioned is a total difference of 6 s between the Limited Torque variant and the variant of Maximum Torque. This difference is roughly the same for single-speed transmission (142 s vs. 136 s) as in the case of using the two-speed transmission (140 s vs. 134.1 s).

The maximum torque variant achieves a higher maximum speed, as the motor has more power. The maximum speeds achieved were 190 kph and 211 kph for the limited and maximum torque variants.

Secondly, using a two-speed transmission instead of a single-speed transmission gives an approximately two-second advantage in the one Aragon lap scenario, which is substantial, especially in the racing environment.

The comparison of single-speed and two-speed transmission results is shown in Figure 5. The figure consists of (from top) vehicle speed, electric motor speed, electric motor mechanical power (maximum of 42 kW in the maximum torque variant, 36 kW in case of limited torque variant), and gear ratio.

It is possible to observe when the gearshifts occur (around RPMs of 4 370), and when looking at the electric motor power graph (the third), there are substantial differences in power used. In most cases, the two-speed transmission variant is allowed to use the motor in areas where it can supply more power. Thus, the vehicle can be faster in the race. With constant torque in motor torque characteristics shown in Figure 6, it is possible to imagine linearly increasing power reaching its maximum as the motor torque starts to decrease. As the limited torque variant reaches its maximum power at this point, it shifts to the second gear shortly after this point is exceeded. The single-speed transmission with shifting impossible is, therefore, a trade-off between higher acceleration and maximum speed. Not only the lap time of the single-speed transmission variant is lower, but also the maximum speed achieved.

5. Conclusions

The 1D simulation model of an electric motorcycle was built. Two scenarios were suggested to assess the differences between single- and two-speed transmissions. It was one lap of racing at the Aragon circuit and a test of acceleration at the 150 m distance. Additionally, two variants of motor controller settings were evaluated: the limited torque variant – representing the realistic (rather conservative) setting, and the maximum torque variant – representing the motor datasheet values.

The optimum gear ratio for a single-speed transmission was suggested based on the experiment's design. The gear ratio was changed in intervals from 1 to 15, and the best results in a one-racing-lap scenario were achieved with a gear ratio in intervals from 2.4 to 4 for the limited torque variant and in intervals from 3.5 to 5.2 for the maximum torque variant.

The results for the acceleration test are derived in the same manner. The best times were achieved in the intervals from 7.4 to 9.4 for the limited torque variant and 7.2 to 8 for the maximum torque variant.

The gear optimization for the two-speed transmission was performed using the Genetic Algorithms method. In the end, one acceptable design (for each of the two torque variants) was chosen to represent the results. The best time lap was 140 s for the limited torque variant and 134.1 s for the maximum torque variant. The limited torque variant got the best results for gear ratios of 4.4 and 3.0 (for the first and second gear) while upshifting and downshifting at 4 367 and 2 360 RPMs. The maximum torque variant achieved the best results with gear ratios of 5.7 and 3.0 (first and second gear) while upshifting and downshifting at 7 730 and 2 537 RPMs.

The maximum speeds achieved in the one race lap scenario were 170.6 and 211.0 kph (limited and maximum torque variant) for single-speed transmission and 177.7 and 211.5 kph (limited and maximum torque variant) for two-speed transmission.

To conclude:

- the difference between limited and maximum torque variants of motor controller setting is around 6 s,
- the possible benefit of a two-speed transmission usage in this vehicle and this scenario is around 2 s per lap,
- maximum torque variant: **the best lap time achieved was 134.1 s** (with two-speed transmission, GR1 = 5.7, GR2 = 3.0),
- maximum torque variant: **the best acceleration time in the 150 m acceleration test was 6.7 s** (with gear ratio of 7.6),
- limited torque variant: the best lap time achieved was 140 s (with a two-speed transmission, GR1 = 4.4, GR2 = 3.0),
- limited torque variant: the best acceleration time achieved was 7.6 s (GR = 8.8).

The benefit of the two-speed transmission over the single-speed transmission is around 2 seconds on a lap, which can be substantial in the racing environment. However, it is not clear if this advantage can balance the higher complexity of the shiftable gearbox system, not only in the higher number of components and added weight, but also in adding the gear shifting mechanism and tuning it to be comfortable for rider use in the stressful and demanding environment that motorcycle racing certainly is.

List of symbols

BEV Battery Electric Vehicle
DOE Design of Experiment
EM Electric Motor
GA Genetic Algorithms
GR Gear Ratio
RPM Revolutions per Minute
SOC State of Charge

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