Efficiency-based Methodology for the Selection of Electric Motors for Mini-tractor Propulsion

Ibraim Alibek
3rd year PhD student
Satbayev University
Department of Mechanical Engineering
Kazakhstan

Absadykov Bakhyt
Associate Professor
Satbayev University
Department of Mechanical Engineering
Kazakhstan

Sanjin Troha
Associate Professor
University of Rijeka
Faculty of Mechanical Engineering
Croatia

Kristina Marković
Associate Professor
University of Rijeka
Faculty of Mechanical Engineering
Croatia

Željko Vrcan
Associate Professor
University of Rijeka
Faculty of Mechanical Engineering
Croatia

This article deals with the research and analysis of electric motors and their matched transmission systems within the context of a versatile electric mini-tractor designed for tasks such as street cleaning, urban park maintenance, and transportation of small loads. The primary objective of the research is to assess the strengths and weaknesses of several electric motor and transmission combinations designed to meet the specific operational demands of the tractor. As the driveline has to provide substantial torque while maintaining optimal operating conditions and avoiding overheating, a series of experiments were conducted, covering various electric motor configurations operating within the 60V range, with power outputs ranging from 1000 to 1500 watts and including multiple gearbox variations. A comparative analysis was performed to assess the advantages and disadvantages of direct chain drive transmission solutions without a differential on a rigid axle, in contrast to a sealed motor-gearbox unit featuring differential and semi-axles. The results of this research were used for mathematical comparison of the driveline solutions, enabling the detection of optimally matched transmission and motor solutions. The experiments also covered the identification of energy-efficient solutions and optimal design parameters for an electric tractor explicitly designed for continuous operation exceeding 10 hours, with cargo capacity exceeding 500 kg, high offroad maneuverability, and a service life exceeding 5000 hours. The dynamic tests carried out during the research have provided valuable insight into the relation of the overall power efficiency of the vehicle to the weight and transmission ratio variations.

Keywords: electric utility vehicle, brushless direct current electric motor, reduction gear, gear transmission, chain drive, efficiency.

1. INTRODUCTION

According to a recent analysis conducted by Rocky Mountain Institute (RMI) in collaboration with the Bezos Earth Fund, global electric vehicle (EV) sales are poised to meet or even surpass the most ambitious net-zero emission goals. It is projected that by 2030, EVs could capture over two-thirds of the market share, following a remarkable trend of exponential growth.

The research conducted by RMI indicates that the sales of traditional internal combustion engine cars had peaked in 2017, and that in the coming years, more of these vehicles will be retired than sold. Consequently, the overall fleet of combustion engine cars is anticipated to peak out and subsequently decline significantly by 2030 [1-4].

This shift is expected to follow an 'S-curve' trajectory that has already been established by leading EV markets in Northern Europe and China. According to this analysis, global EV sales are set to increase at least sixfold by 2030, accounting for a market share ranging from 62% to 86% of new vehicle sales. This contrasts with current projections, which only foresee EVs capturing around 40% of the market share by 2030, despite frequent upward revisions to accommodate the ongoing exponential growth [1-3].

Given that internal combustion engine cars contribute to approximately a quarter of global oil demand, with road transport as a whole accounting for nearly half, the rapid growth of EVs poses a significant threat to oil demand. According to RMI's forecasts, oil demand for cars reached its peak in 2019 and is expected to decline by at least one million barrels per day (mbpd) annually after 2030, effectively negating any anticipated growth in oil demand for cars [1-3].

The analysis highlights that economics are now becoming the primary driver of EV sales, surpassing policy incentives. This shift is primarily attributed to the declining costs of batteries, with RMI anticipating that battery costs will be halved within this decade, dropping from \$151 per kilowatt hour (kWh) to a range of \$60 to \$90 per kWh by 2030 [5]. As a result, decreasing costs will make EVs, for the first time, competitively priced with or cheaper to both purchase and operate compared to traditional petrol cars across all global markets [6].

Received: February 2024, Accepted: May 2024
Correspondence to: Željko Vrcan
University of Rijeka - Faculty of Engineering,
Vukovarska 58, HR-51000 Rijeka, Croatia
E-mail: zeljko.vrcan@riteh.uniri.hr
doi: 10.5937/fme2403360A

The expected dominance of EVs in car sales is also projected to lead to electrification in other modes of road transport, including two- and three-wheelers as well as heavy-duty trucks [7]. By proximity, all-terrain vehicles (ATVs) are not immune to the rapid electrification sweeping the auto industry. The desire for a cleaner environment has forced manufacturers to look beyond traditional petrol-powered ATVs, resulting in multiple environmentally friendly all-terrain vehicles equipped with electric powertrains available on the market.

The electric motor used in electric vehicles provides maximum torque from the standstill to the redline. When compared to internal combustion engines on classic vehicles, the electric motor is self-starting and does not need to idle when the vehicle is stationary [5].

The development of electric motors and transmissions has reached the point where efficiency exceeds 90% [8,9]. The efficiency of any electric motor is reduced under load, depending on the type of electric motor and transmission. Transmission losses account for about 1-5% of total power output [10, 11]. However, the losses may be reduced by the application of specially crafted transmission solutions [12].

The rise of electric vehicles, known for their environmental friendliness, efficiency, and minimal maintenance, is driving increased research into optimizing their performance. The right selection of the electric motor is critical, focusing on simplicity, high power output, minimal maintenance costs, and ease of control [13-15]. Electric vehicles employ various motor types, such as brushed DC motors, brushless DC motors, induction motors, permanent magnet synchronous motors, and switched reluctance motors, depending on the designer's preference [16,17].

The main subject of the article is research into the efficiency of EV motors and drivetrains. Their theoretical energy efficiency is high, so these experiments and research will test how much of it is correct. The vehicle power efficiency is measured through input power and output power and by how much they change under load. A BLDC (Brushless DC) electric motor was chosen for the research due to its high efficiency. The experiments were performed using 60 V BLDC motors in the 1-1,5 kW range, with chain drivetrains and two-step gear–boxes. The tests will show the actual efficiency of the electric motors by comparing the electric power supp–lied to the motor with the power transferred to the dri–ving wheels, showing the real efficiency of the electric driveline. Two of the most popular gearbox systems that have been tested are chain and sprocket and geared transmission. It should also be said that electric vehicles have some other places with efficiency losses, i.e., battery, controller, electric motor, transmission, and wheels. A fully charged Li-Ion battery of 67,2 V output was used (fully charged 60 V battery), and the overall efficiency of the system, measured using a single 5 kW motor controller, was found to be in the 97-98% range [18].

Attempts to calculate the efficiency of BLDC motors have been performed, and methods for the computation of power losses have been discovered. [18-20].

In [19], the JAYA algorithm for the determination of global optima was used to determine the optimal parameters of a brushless DC motor by applying the theory of electromagnetic structure parameter selection and efficiency calculation. The optimal design obtained by this procedure is closest to the optimum, respecting both the mechanical and electrical constraints of the application.

In [20], analysis and simulation were applied to a BLDC motor in order to develop an efficiency map of the motor used as a traction motor for an electric vehicle. Extensive simulation and calculations were performed, with good results for the electrical part, however no attempt was made to model the losses in the mechanical part of the transmission.

The analysis of the BLDC electric motor efficiency and of different gearbox types based on the design framework of an electric tractor / ATV (All-Terrain Vehicle) [21] was undertaken to explore how different combinations of motor and transmission impact the efficiency of electric vehicles with and without load [22]. The research on methodology for the selection of BLDC electric motors and transmission solutions based on overall system efficiency, as laid out in this paper, is expected to have practical applications in various fields of engineering.

For example, suppose the power loss under load is correctly calculated. In that case, it will be possible to correctly calculate the running time and range of electric vehicles (EVs) using BLDC motors, such as small cars, ATVs, tractors, scooters, and e-bicycles.

Another area of application where improvements are expected is the area of industrial machinery, robots, and automation, where it will become possible to select the appropriate transmission and motor type to reduce energy losses. Finally, improvements could be made in the area of agricultural machinery to reduce power losses and improve the operating range of battery-powered equipment.

To sum up, it is expected that the main contribution to engineering practice will consist of insights for the design of improved and reliable power-efficient transmission systems.

2. TESTING AND EFFICIENCY CALCULATION OF ELECTRIC MOTOR AND TRANSMISSION

The tests involved two types of 60 V DC electric motors rated at 1000 and 1500 watts with similar characteristics and using identical mounts. The declared no-load speeds are 4700 and 3700 min^{-1}, with motor weights of 10,2 and 11,1 kg, respectively. Although these motors appear visually and dimensionally similar, they exhibit different torque and rotational speed range characteristics.

Both motors belong to the category of BLDC (Brushless DC) motors, known for their superior efficiency and specific power compared to traditional DC motors. However, they are susceptible to irreversible demagnetization and coil insulation damage under severe thermal conditions. Hence, accurately predicting heat losses and real-time temperature distribution in drive motors is crucial [23].

Multiple tests were conducted to detect motor overheating under various loads commonly encountered in mini tractors and ATVs. ATVs are small, motorized vehicles, typically four-wheeled, designed for adverse terrain navigation. They serve recreational, sporting, and commercial purposes, such as agriculture or log–

ging, requiring heavy load capacity, high cross-country capabilities, and reliability.

Several types of transmission are employed in ATVs depending on the purpose, including chain, belt, infi–nitely variable, and mechanical geared transmission. This study is focused on cost-effective methods for connecting an electric motor to a gearbox, such as a chain and sprocket transmission, geared drive, and a mechanical two-speed gearbox with differential gear final drive [24].

Table 1 shows a comparison detailing key features, with a primary focus on reliability, price, and ease of maintenance.

Table 1. Comparison of two types of transmission

Characteristic	Chain transmission	Gearbox with differential
Gear ratio	Determined by the number of the teeth of the large sprocket	Determined by selecting the gear pair
Connection of the wheels	Rigid axle	Independent semi-axles
Noise	Loud without tensioners	Quiet
Changing the gear ratio during operation	No	Yes
Durability	2-3 years	More than 5 years
The price	Relatively inexpensive	Expensive

A chain transmission and a geared transmission are two different types of mechanisms used to transfer power from the engine to the wheels of a vehicle. Here are some of the main differences between them:

Design: A chain transmission uses a chain to transfer power from the engine to the wheels, and a geared transmission uses a series of gears [25, 26].

Efficiency: A chain transmission is generally less efficient than a geared transmission because some of the energy is lost due to friction between the chain and the sprockets. On the contrary, geared transmission is more efficient because it uses gears that engage with each other, resulting in reduced power loss [21].

Maintenance: A chain transmission requires more maintenance than a transmission with a gearbox because the chain needs to be lubricated and adjusted regularly. On the other hand, a geared transmission requires less maintenance since the gears are closed and do not require special attention [22,26].

Cost: A chain transmission is generally cheaper than a transmission with a gearbox, both in terms of initial cost and in terms of maintenance costs over time [28].

Application: Chain transmissions are often used in off-road vehicles, such as off-road motorcycles and ATVs, as they are more durable and can overcome rough terrain. Transmissions with a gearbox are com–monly used in passenger cars, where smoother driving and greater fuel efficiency are required [29].

2.1 Driveline 1 – single-stage chain

The first tested option is a single-stage chain trans–mission without a chain tensioner, as seen in Figure 1. A standard motorcycle chain type 428 with a set of sprockets was chosen – driving sprocket z_{1sc}=15 teeth and driven z_{2sc}=45 teeth, resulting in a transmission ratio of i_{sc}=3.

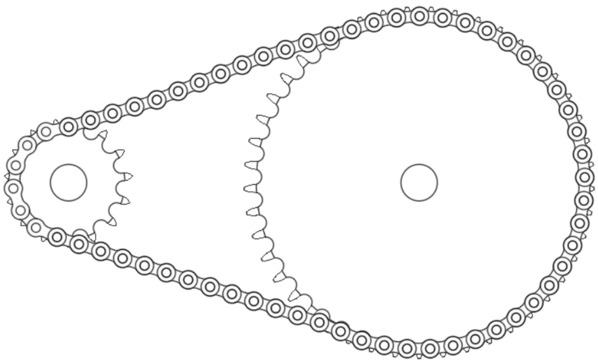


Figure 1. Side view of single-stage chain driveline

Motor EM 1 (P_{motor}=1,5 kW, Table 2) was used for the first set of tests. The vehicle was able to achieve v_{DL1}= 48,1 km/h with the motor installed. The BLDC motor reaches a top rotational speed of $n_{EM1,\,DL1ul}$= 555 min^{-1} as shown in Table 3, but the vehicle experiences a prolonged acceleration, about 2 minutes, with the motor developing full power, meaning that the torque was inadequate for the mass of the vehicle. The tests were performed with the vehicle ballasted to 200 kg, the 105 kg extra weight being distributed between the driver and additional weights. The speed was measured in real-time on a flat surface and using a GPS navigator. Electrically, it was assumed that the motor and its associated control electronics constitute a “black box”, and voltage/current measurements were made at the control electronics input terminals.

Table 2. Main parameters of electric motor EM 1

Power - P_{EM1}	1500 W
Peak power - P_{EM1p}	≈ 2200 W
Peak torque - T_{EM1p}	5 Nm
Mass - m_{EM1p}	3,4 kg
No load speed - n_{EM1nl}	3770 min^{-1}
Rated voltage - U_{EM1}	60 V
Maximum voltage - U_{EM1max}	67,2 V
Rated current - I_{EM1}	25 A
Maximum current - I_{EM1max}	32 A

Table 3. Test parameters used for Driveline 1

Number of driving sprocket teeth – z_{1sc}	15
Number of driven sprocket teeth – z_{2sc}	45
Transmission ratio - i_{sc}	3
Wheel rotational speed (no load) - $n_{EM1,\,DL1nl}$	1254 min^{-1}
Wheel rotational speed (100 kg load) - $n_{EM1,\,DL1ul}$	555 min^{-1}
Wheel size	R12 18X9.50-8
Wheel diameter - d	0,46 m
Tractor mass	95 kg
Total (ballasted) mass	200 kg

The overall power efficiency η_{sc} may be calculated as the ratio of power output to power input (1) using

$$\eta = \frac{P_{out}}{P_{in}} . \qquad (1)$$

Input power in (1) equals electrical power, while output power equals mechanical power (2) [29]:

$$\eta = \frac{P_M}{P_E} . \qquad (2)$$

Mechanical power is calculated as (3):

$$P_{M,EM1} = \frac{2\pi T_{EM1p} n_{EM1}}{60} = 1972,97\ W . \qquad (3)$$

Electrical power is calculated as (4):

$$P_{E,EM1} = U_{EM1max} I_{EM1max} = 2150,4\ W . \qquad (4)$$

The total no-load motor efficiency was then calcu– lated as η_{em} =91,75%. In the next step, mechanical effi– ciency under no load with the driving wheels jacked up was calculated. The motor power in this case is (5):

$$P_{EM1,DL1nl} = \frac{2\pi T_{EM1p} i_{sc} n_{EM1,DL1nl}}{60} = 1968,78\ W . \qquad (5)$$

The efficiency of the electric drive under no-load conditions equals (6):

$$\eta_{EM1,DL1nl} = \frac{P_{EM1,DL1nl}}{P_{E,EM1}} = 91,55\% . \qquad (6)$$

The overall mechanical efficiency under no-load conditions equals (7):

$$\eta_{EM1,DL1nl(Mech)} = \frac{P_{EM1,DL1nl(Mech)}}{P_{M,EM1}} = 99,78\% . \qquad (7)$$

The vehicle was then loaded with 105 kg of driver and ballast. The tests were repeated for no-load condi– tions. The mechanical efficiency under load is calcu– lated as (8):

$$P_{EM1,DL1ul} = \frac{2\pi T_{EM1p} i_{sc} n_{EM1,DL1ul}}{60} = 871,35\ W . \qquad (8)$$

The efficiency of the electric drive under load (9) is calculated in a manner similar to (6):

$$\eta_{DL1,ul} = \frac{P_{EM1,DL1,ul}}{P_{E,EM1}} = 40,52\% . \qquad (9)$$

The overall mechanical efficiency under load (10) is calculated following the pattern from (7):

$$\eta_{EM1,DL1ul(Mech)} = \frac{P_{EM1,DLul(Mech)}}{P_{M,EM1}} = 44,16\% . \qquad (10)$$

The electrical efficiency under load (11) is calcu– lated as the ratio of the power developed by the motor under no load and the power developed under load:

$$\eta_{E,EM1,DL1} = \frac{P_{EM1,DL1ul}}{P_{EM1,DL1nl}} = 44,26\% . \qquad (11)$$

From the results, it is obvious that there is a large energy loss of 60% due to a lack of motor torque (9). After taking into consideration that the efficiency of the chain transmission fluctuates around 99,79%, [30] it was concluded that this energy loss is converted into heat, leading to the electric motor overheating. During the first tests, the motor was heated to 90 ^{0}C, although this might be partly related to the motor having an S2 class rating. According to the documentation, the opti– mal operating temperature of the electric motor is 30-50 ^{0}C [31, 32]. The motor overheats under heavy load, and with prolonged operation, the motor windings could burn out. In this case, it is impossible to reach high transmission efficiency, which was one of the main research objectives, as roughly 60% of the input power is lost as heat. This solution should probably be avoided as the acceleration time is an unacceptable 70 seconds.

2.2 Driveline 2 – two-stage chain

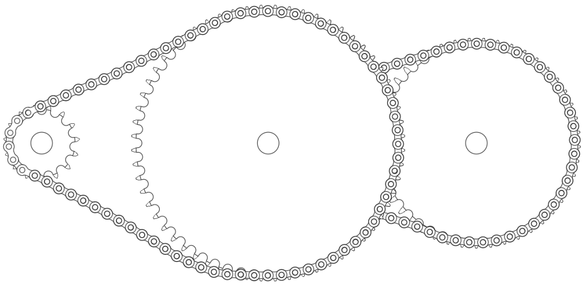
The second tested option is a two-stage chain trans– mission without chain tensioners. A standard motor– cycle chain type 428 with a set of sprockets was chosen – the first driving sprocket z_{11dc} = 15 teeth, driven sprocket z_{21dc} = 60, resulting in a transmission ratio of 4, and the second driving sprocket z_{12dc} = 15, driven sprocket z_{22dc} = 45, resulting in a transmission ratio of 3 as shown in Figure 2. The overall transmission ratio is i_{dc} = 12. Figure 2 also shows the overall structure of the transmission with the intermediate shaft and the two stages.

Tests were performed with motor EM 1 installed (Table 2), and the main test parameters are shown in Table 4.

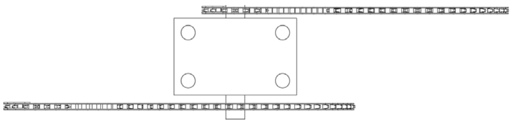
Table 4. Test parameters used for Driveline 2

Number of Stage 1 driving sprocket teeth – z_{11dc}	15
Number of Stage 1 driven sprocket teeth – z_{12dc}	60
Number of Stage 2 driving sprocket teeth – z_{12dc}	15
Number of Stage 2 driven sprocket teeth – z_{22dc}	45
Overall transmission ratio - i_{dc}	12
Wheel rotational speed (no load) - $n_{EM1,\ DL2nl}$	335 min^{-1}
Wheel rotational speed (100 kg load) - $n_{EM1,\ DL2ul}$	246 min^{-1}
Wheel size	R12 18X9.50-8
Wheel diameter - d	0,46 m
Tractor mass	120 kg
Total (ballasted) mass	500 kg

The maximum speed of the tractor decreased to v_{DL2}= 27 km/h, the acceleration time was significantly shortened, and the 5 Nm of torque on the motor was increased to 56,25 Nm at the output. This was enough to pull more than 500 kg of weight without issues in the second experiment (120 kg tractor mass, plus driver and ballast totaling 500 kg). In this case, the motor began to work under load in the recommended range of 30-45 ^{0}C, and the measured electrical load on the controller and wires was also reduced. The photos of the transmission assembly are shown in Figure 3 and Figure 4. The speed was measured in real-time on a flat surface and using a GPS navigator.



(a)



(b)

Figure 2. Two-stage chain: (a) side view and (b) top view

As in the case of Driveline 1, the mechanical motor power is $P_{M,EM1}$ = 1972,97 W and the electrical motor power is $P_{E,EM1}$ = 2150,4 W, resulting in a total no-load motor efficiency of η_{em} =91,75%.

The mechanical efficiency under no load with the driving wheels jacked up (12) is calculated in a manner similar to (5):

$$P_{EM1,DL2nl} = \frac{2\pi T_{EM1p} i_{dc} n_{EM1,DL2nl}}{60} = 1972,31\,\mathrm{W} \quad (12)$$

Figure 3. Two-stage chain, front view

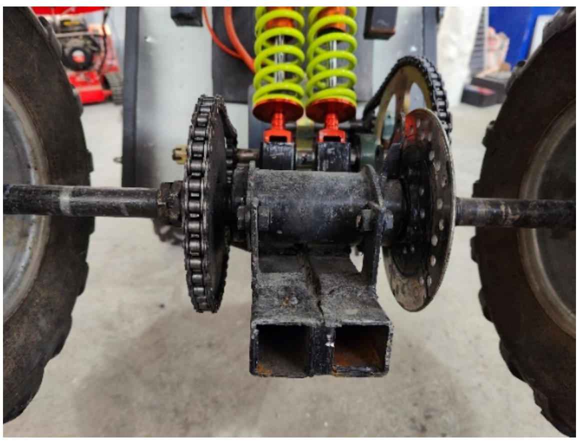


Figure 4. Two-stage chain, back view

The efficiency of the electric drive under no-load conditions equals (13):

$$\eta_{EM1,DL2nl} = \frac{P_{EM1,DL2nl}}{P_{E,EM1}} = 91,73\% . \quad (13)$$

The overall mechanical efficiency for this trans–mission under no-load conditions equals (14):

$$\eta_{EM1,DL2nl(Mech)} = \frac{P_{EM1,DL2nl(Mech)}}{P_{M,EM1}} = 99,96\% . \quad (14)$$

As with Driveline 1, the vehicle was then loaded with driver and ballast, and the tests were repeated for no-load conditions. The mechanical efficiency under load is calculated as (15):

$$P_{EM1,DL2ul} = \frac{2\pi T_{EM1p} i_{dc} n_{EM1,DL2ul}}{60} = 1448,32\,\mathrm{W}. \quad (15)$$

The efficiency of the electric drive under load (16) is calculated in a manner similar to (6) and (13):

$$\eta_{DL2,ul} = \frac{P_{EM1,DL2,ul}}{P_{E,EM1}} = 67,32\% . \quad (16)$$

The overall mechanical efficiency under load (17) is calculated following the pattern from (7) and (14):

$$\eta_{EM1,DL2ul(Mech)} = \frac{P_{EM1,DL2ul(Mech)}}{P_{M,EM1}} = 73,41\% . \quad (17)$$

The electrical efficiency under load (18) is calcu–lated as the ratio of the power developed by the motor under no load and the power developed under load:

$$\eta_{E,EM1,DL2} = \frac{P_{EM1,DL2ul}}{P_{EM1,DL2nl}} = 73,43\% . \quad (18)$$

From the results, it is obvious that the electrical losses have become considerably lower (about 33%) as the motor can develop and maintain its rated torque. Unlike the first test, the motor reaches its optimal operating temperature and remains stable at 45 °C or less. This solution is viable as power losses amount to 33% of the total input.

2.3 Driveline 3 – geared transmission

The third tested option is the factory default gearbox (Figure 5) with a geared differential and the possibility of switching between two mechanical gears. This option uses the default 1kW electric motor EM 2 (Table 5), which allows the tractor to reach the maximum speed v_{DL3}= 41 km/h.

This motor and transmission setup also fulfills the requirement to transport 500 kg without issues. The average temperature of the motor working under load was found to be in the range of 40-45 °C. This motor has a lower torque output of 4 Nm, which is achieved at a higher rotational speed of 4724 min^{-1}. The default gearbox has 2 mechanical gear ratios: a high gear with a transmission ratio of i_{HG} = 8,36 and a low gear with a transmission ratio of i_{LG} = 20,54. This gear increases the torque to 82,16 Nm, which allows the machine to pull more than 500 kg. The gear ratio is selected with the stationary vehicle by physically shifting the gears within the drive [28]. The overall efficiency of this layout was found to be around 70-77%, depending on the trans–mission.

Table 5. Main parameters of electric motor EM 2

Power - P_{EM2}	1000 W
Peak power - P_{EM2p}	≈ 2200 W
Peak torque - T_{EM2p}	4 Nm
Mass - m_{EM1p}	3,2 kg
No load speed - n_{EM2nl}	4724 min^{-1}
Rated voltage - U_{EM2}	60 V
Maximum voltage - U_{EM2max}	67,2 V
Rated current - I_{EM2}	25 A
Maximum current - I_{EM2max}	32 A

Figure 5. Two-speed gearbox with differential

An overview of the rear axle arrangement is shown in Figure 6, while the test parameters are listed in Table 6.

The mechanical power of the motor (19) is calcu–lated as in the case of (3):

$$P_{M,EM2} = \frac{2\pi T_{EM2p} n_{EM2}}{60} = 1977,78\text{ W} . \qquad (19)$$

Electrical power is calculated as (20):

$$P_{E,EM2} = U_{EM2\max} I_{EM2\max} = 2150,4\text{ W} . \qquad (20)$$

The total no-load motor efficiency was η_{em} = 91,97%.

The mechanical efficiency for operation of Motor 2 with Driveline 3 under no load with the driving wheels jacked up was then calculated for operation in low gear (21,23,25) as well as for operation in high gear (22,24,26):

$$P_{EM2,DL3nlLG} = \frac{2\pi T_{EM2p} i_{LG} n_{EM2,DL3nlLG}}{60} = 1977,53\text{W} \quad (21)$$

$$P_{EM2,DL3nlHG} = \frac{2\pi T_{EM2p} i_{HG} n_{EM2,DL3nlHG}}{60} = 1969,26\text{W} \quad (22)$$

The efficiency of the electric drive under no-load conditions for Driveline 3 in low and high gear equals (23,24):

$$\eta_{EM2,DL3nlLG} = \frac{P_{EM2,DL3nlLG}}{P_{E,EM2}} = 91,96\% . \qquad (23)$$

$$\eta_{EM2,DL3nlHG} = \frac{P_{EM2,DL3nlHG}}{P_{E,EM2}} = 91,57\% . \qquad (24)$$

The overall mechanical efficiency for Driveline 3 under no-load conditions for low and second gear equals (25,26):

$$\eta_{EM2,DL3nlLG(Mech)} = \frac{P_{EM1,DL3nlLG(Mech)}}{P_{M,EM2}} = 99,987\% . \; (25)$$

$$\eta_{EM2,DL3nlHG(Mech)} = \frac{P_{EM2,DL3nlHG(Mech)}}{P_{M,EM2}} = 99,57\% . \; (26)$$

The loaded test was performed with the vehicle ballasted to 200 kg for both gears, as the vehicle was unable to move from a standstill in high gear when ballasted to 500 kg.

By appropriately modifying equations (19-26), the following results were calculated for Driveline 3 (Table 7):

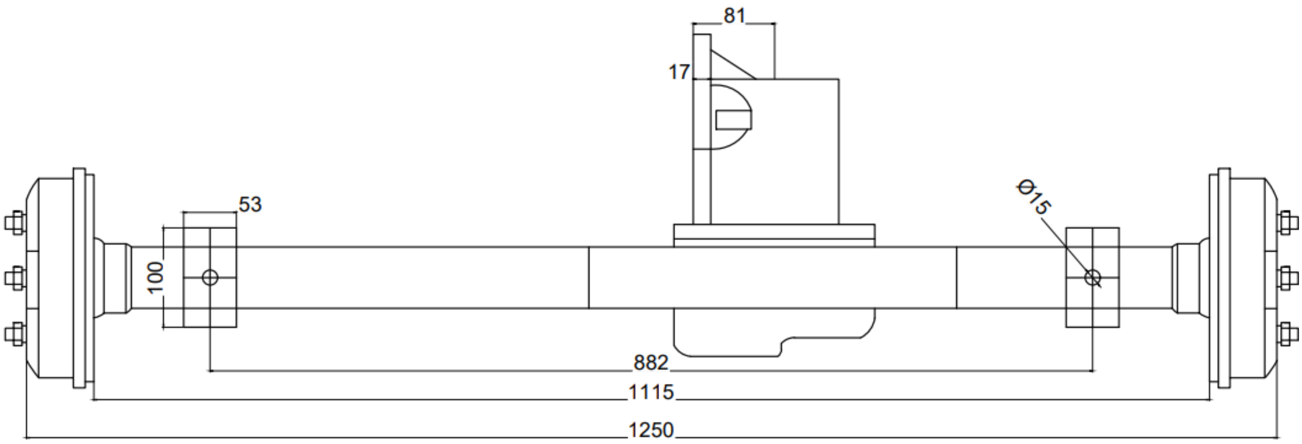


Figure 6. Rear axle arrangement

Table 6. Test parameters used for Driveline 3

Low gear transmission ratio – i_{LG}	20,54
High gear transmission ratio – i_{HG}	8,36
Wheel rotational speed, no load, high gear - $n_{EM2,DL3nlHG}$	565 min^{-1}
Wheel rotational speed, full load, high gear - $n_{EM2,DL3ulHG}$	423 min^{-1}
Wheel rotational speed, no load, low gear - $n_{EM1,DL2nlLG}$	229 min^{-1}
Wheel rotational speed, full load, low gear - $n_{EM1,DL2ulLG}$	177 min^{-1}
Wheel size	R12 18X9.50-8
Wheel diameter - d	0,46 m
Tractor mass	95 kg
Total (ballasted) mass	200 kg

Table 7. Performance under load for Driveline 3

Motor power in low gear under load - $P_{EM2,DL3ulLG}$	1480,52 W
Motor power in high gear under load - $P_{EM2,DL3ulLG}$	1522,1 W
Mechanical efficiency in low gear under load – $\eta_{EM2,DL3ulLG(Mech)}$	91,96%
Mechanical efficiency in high gear under load - $\eta_{EM2,DL3ulHG(Mech)}$	91,97%
Electrical efficiency in low gear under load - $\eta_{E,EM2,DL3ulLG}$	74,87%
Electrical efficiency in high gear under load - $\eta_{E,EM2,DL3ulLG}$	76,96%
Overall efficiency in low gear under load – $\eta_{EM2,DL3ulLG}$	68,75%
Overall efficiency in high gear under load - $\eta_{EM2,DL3ulHG}$	70,78%
Efficiency ratio for low gear load/no load - $\eta_{EM2,DL3nl/ulLG}$	74,87%
Efficiency ratio for high gear load/no load - $\eta_{EM2,DL3nl/ulHG}$	77,29%

3. DATA ANALYSIS AND RESEARCH OF EFFICIENCY PATTERNS

The efficiency of the BLDC electric motor depends on the gear ratio, gearbox type, and vehicle mass. As the motors evaluated for the purposes of this paper are used in three-wheelers and ATV machines used for the transportation of goods, the motors are given inconsistent treatment by the manufacturers, and in most cases, it is unclear whether the nominal or the peak power output has been declared. The quality of the components, combined with the build quality, is important in the design of goods and vehicles. The tests performed during the research presented in this article have shown that BLDC motors are capable of sustained operation in their nominal power range with 130-150% short-term output peaks. However, under continuous heavy load, there is a drop in power output of about 30% with an efficiency of nearly 70%. The BLDC motors with nominal power in the 1000 to 1500 W range used in this article have peak ratings exceeding 2000 W, meaning that a power reserve of 30…50% has been built into these motors.

It is common for electric vehicle manufacturers to state an overall efficiency of around 90%. However, this does not take into account the other factors that may influence the result, such as the main battery charge level, cell type, and condition, voltage drop on motor terminals under load, electric motor type, resistive, capacitive, inductive, and magnetic motor losses, and finally the efficiency of the power controller electronics and its associate parts.

The overall no-load efficiency was observed to be about 90-92%, proving that the system is well-designed. The mechanical transmission efficiencies are more than 95%, the efficiency of the electric motors under no load is over 97%, and the efficiency of the whole system is around 90%, proving that the system is well designed. When ballasted to 200 kilograms, the losses with the smaller gear ratio are considerably higher, resulting in an overall efficiency of around 47% for the first drive–line. This means that the appropriate selection of gear ratios, as with drivelines 2 and 3, can result in the effi–ciency of driveline 1 being increased to 70…75%. A direct relation between the increase in total vehicle mass and the decrease in efficiency was observed for Drive–line 1 (Figure 7), complete with decreased electric mo–tor performance and a considerable increase in waste heat generation.

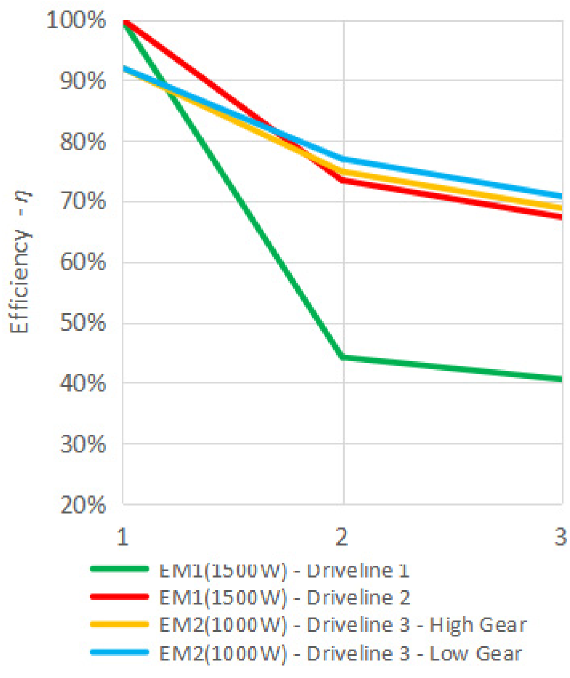


Figure 7. Variation of vehicle efficiency: 1 – Only mecha–nical losses (wheels jacked up); 2 – Mechanical efficiency when ballasted to 200 kg; 3 – Electrical efficiency when ballasted to 200 kg.

The same issue was observed with the other drive–lines but much less pronounced.

Even though the two motors under test have a similar peak power output, their torque and rpm charac–teristics differ, but this can be amended with the correct selection of the transmission ratio, as energy efficiency was observed to increase with high transmission ratios due to lower ohmic losses [34]. It was observed from the reduction in vehicle efficiency exhibited in Figure 8 that electric motors experience a serious efficiency loss in cases when the motor power and transmission ratio are not correctly matched to the load, but this can be partly mitigated with a good torque curve and a high-performance transmission.

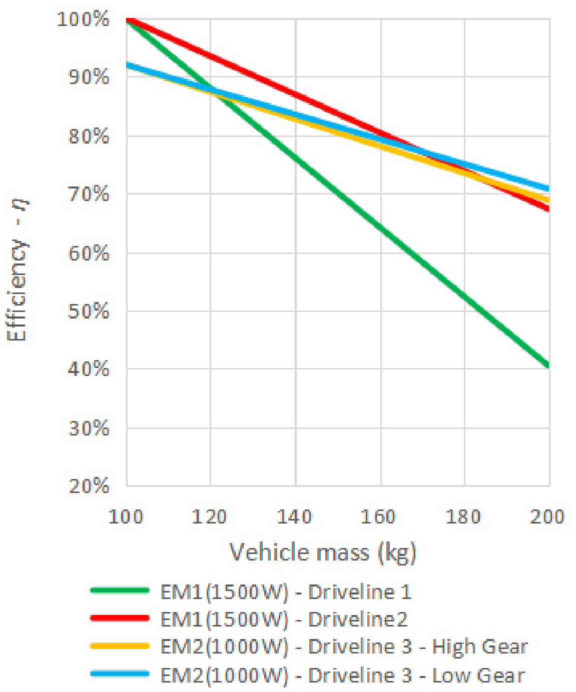


Figure 8. Reduction of efficiency under load: 1 – No load (wheels jacked up); 2 – 100 kg load and vehicle weight.

It was observed that the single-stage chain trans–mission is underpowered, while the two-stage chain and factory-built geared transmissions provide adequate per–formance. The overall efficiency of the two-stage chain transmission (67,35%) was found to be very close to the efficiency of the factory standard gearbox (68.84% in high gear and 70,78% in low gear). This has also con–firmed that the original transmission in the form of a two-speed gearbox with differential presents a sound solution.

Finally, it was observed that the BLDC electric motor is one of the most energy-efficient motor soluti–ons, as it exhibits electrical no-load efficiencies beyond 90% in all cases. However, this type of motor can expe–rience a very serious internal loss of up to about 45% if the motor is not properly matched to the transmission.

4. CONCLUSION

Due to the impact of power usage and efficiency on the operating range of battery-electric vehicles, it is very important to research the efficiency and characteristics of electric motors and their associated drivetrains.

Several drivetrain options are available, combining an electric motor with chain or geared drive. Several types of electric motor may be used, such as permanent magnet synchronous, induction and switched reluctance, however brushless DC (BLDC) motors are preferred because they offer a good torque characteristic and perform well at low RPM.

The electrical part of the traction system tested in this article uses a 5 kWh Li-ion battery connected to a 1 kW motor in one case and to a 1,5 kW motor in the other case. The motors were connected using their appropriate controllers. The mechanical transmissions tested consisted of a single-stage chain, two-stage chain, and geared axle two-speed setup. Testing has shown that the mechanical efficiency of the chain and gear drives is in the 95-99% range and that the overall efficiency of BLDC electric vehicles is primarily determined by the electrical part of the vehicle, with the actual efficiency under load being about 70%.

The motors were observed to develop short-term peaks of 2200 W, meaning that the larger motor can be overloaded to 150% of its rated power for a short time, while the smaller motor may develop up to 220% of its rated power.

The single-stage chain transmission was tested using the larger motor. In this case, it was found that the mechanical efficiency of the drive is about 99% and that the no-load electrical efficiency of the drive is about 92%. However, things rapidly change when the vehicle is loaded up to test requirements when its electrical efficiency drops to about 44%. This was discovered to be due to the transmission ratio being too high for the operating range of the electric motor, resulting in very high electrical losses.

The two-stage chain transmission was tested using the larger motor and found to be adequate, stressing the need for proper matching of the motor and mechanical transmission. The mechanical efficiency of the driveline was found to be about 99%, while the no-load electrical efficiency of the drive was also found to be about 92%, with a small difference most likely due to the different sprocket installation. However, the electrical efficiency was found to be an acceptable 73% due to the motor now running within its design parameters.

The two-speed gearbox with differential and rigid axle unit was tested with the smaller motor. It was found to have a mechanical efficiency of about 92% in both gears. This was expected as the drive unit combines several gear pairs in a gearbox. Electrically, the no-load efficiency was about 92% in both cases. Under load, the electrical efficiency was found to be about 75% in low gear and about 77% in high gear, pointing to the fact that the transmission was properly matched to the electric motor. However, the smaller motor probably has a slightly different characteristic in comparison to the larger motor.

The purpose of these experiments was to detect high-efficiency motor-to-gearbox pairings. The results suggest that the highest efficiency in laboratory conditions will be obtained when using a matched two-stage chain drive, however, in practical applications priority should be given to the enclosed axle with motor and gearbox unit, as it operates as a sealed unit with virtually unchanged efficiency regardless of the environment, while also providing a solution of increased reliability.

Power efficiency is a key discipline for the development and manufacture of electric vehicles. A proper calculation of the components combined with high build quality is paramount to a good electric vehicle, as most manufacturers state a number more than 90% obtained in ideal lab conditions without loaded testing and stress testing. Testing under stress, as proposed in this paper, exposes other factors, such as battery condition and type, while the pairing of the motor and controller is also considered as it directly determines the drive efficiency under load.

It is expected that the methodology proposed in this paper will be of assistance in the design of efficient driveline solutions for electric vehicles such as cars, bicycles, scooters, mini tractors, aircraft, boats, drones or just any electrical project that requires high efficiency electric drives.

ACKNOWLEDGMENT

The research in this paper is part of the “Development of a modular multifunctional electric mini tractor" startup project, funded by the Kazakh National Research Technical University, named after K. I. Satbayev, r. n. RNNTD22RKI052.

REFERENCES

[1] Kingsmill B. et al.: X-change: Cars - The end of the ICE age, Rocky Mountain Institute, Boulder, CO, 2023.

[2] Corradi, C., Sica, E. and Morone, P.: What drives electric vehicle adoption? Insights from a systematic review on European transport actors and behaviours. Energy Research & Social Science, Vol. 95, 2023, 102908, 10.1016/j.erss.2022.102908.

[3] Lenton, T.M. et al.: Operationalising positive tipping points towards global sustainability, Global Sustainability, Vol. 5, p. e1, 2022, 10.1017/sus. 2021.30.

[4] Pisarov, J. and Mester, G.: The Future of Autonomous Vehicles, Vol. 49 No. 1, 2021, pp. 29-35, 10.5937/fme2101029P.

[5] Zhang, L., Zhang, C., Horng, J.-H. and Chen, Z.: Study on Simulation of the Chain Transmission Mechanism. Advanced Materials Research, Vol. 593, No. 6, pp. 797-800, 2012.

[6] Kumar, R.R. and Alok, K.: Adoption of electric vehicle: A literature review and prospects for sustainability, Journal of Cleaner Production, Vol. 253, 2020, 119911, 10.1016/j.jclepro.2019.119911.

[7] Chang, C.-M. and Siao, J.-C.: Performance Analysis of EV Powertrain system with/without transmission, World Electric Vehicle Journal, Vol. 4, pp. 629-634, 2010.

[8] Vamsi, G.D.S., Sheriff, M.A. and Raju, J.S.: A Comprehensive Review on the Transmission System of Electrical All-Terrain Vehicle, *IOP Conf. Series: Materials Science and Engineering,* 9-10.10.2020. 2020, Warangal, India 981, 032092, 10.1088/1757-899X/981/3/032092.

[9] He, J.-H., Yang, Q., He, C.-H. and Alsolami, A.A.: Pull-Down Instability of the Quadratic Nonlinear Oscillators, Facta Universitatis, Series: Mechanical Engineering, Vol. 21, No. 2, pp. 191-200, 2023, 10.22190/FUME230114007H.

[10] Sun, X., Li, Z., Wang, X. and Li, C.: Technology development of electric vehicles: A review, Energies, Vol. 13, No.1, pp. 1–29, 2019, 10.3390/ en13010090.

[11] Gayen P.K., Dhara P.K., Das S. and Shrivastav A.: Adaptive shoot-through duty ratio control methodology of stand-alone quasi Z-source inverter, Engineering Review, Vol. 43, No. 3, pp. 101-114, 2023, 10.30765/er.2251.

[12] Kalmaganbetov, S. A. et al.: Selection of Optimal Planetary Transmission for Light Electric Vehicle Main Gearbox, J. Appl. Comput. Mech., 2024, 10.22055/jacm.2024.46280.4490

[13] Shen, Y., Zhu, C., and Wang, X.: Slot Optimization Design of Induction Motor for Electric Vehicle, Material Science and Environmental Engineering, 15–17.12.2017., Xiamen, Chinadoi, Vol. 301, 012081, 10.1088/1757-899X/301/1/012081.

[14] Chebabhi, A., Barkat, S. and Kessal, A.: Combined voltage oriented control and direct power control based on backstepping control for four-leg PWM rectifier under unbalanced conditions, Engineering Review, Vol. 42, No. 3, pp. 86-103, 2022, 10.30765/er.2020.

[15] Milićević, S. V., Blagojević, I. A. and Muždeka, S. R.: Advanced Rule-based Energy Management for Better Fuel Economy of Hybrid Electric Tracked Vehicle, FME Transactions, Vol. 49, pp. 711-718, 2021, 10.5937/fme2103711M.

[16] Hanselman, D.: *Brushless Permanent-Magnet Motor Design*, McGraw-Hill, New York, NY, USA, 1994.

[17] Perišić, N. B. and Jovanović, R. Ž.: Control of Direct Current Motor by Using Artificial Neural Networks in Internal Model Control Scheme, FME Transactions Vol. 51, pp. 109-116, 2023, 10.5937/fme2301109P.

[18] Vorobyev, N.V.: *Tsepnye peredatshi*, Mashino-stroeniye, Moscow, Russia 1968.

[19] Cheng, Y., Lyu, X. and Mao, S.: Optimization design of brushless DC motor based on improved JAYA algorithm, Scientific Reports Vol. 14, 5427, 2024, 10.1038/s41598-024-54582-z

[20] Popescu, L. and Stanescu, A.: Efficiency maps for an EV BLDC motor using analytic calculation and simulation, APME — Electric Machines, Materials and Drives, Vol. 18, No. 1, pp.89‒99, 2022, 10.36801/apme.2022.1.11.

[21] Mevey, J.-R.: *Sensorless field oriented control of brushless permanent magnet synchronous motors*, MSc thesis, Kansas State University, Manhattan, KS, 2006.

[22] Troha S., Vrcan, Ž., Stefanović-Marinović J. and Sedak, M.: Comparison of the size and efficiency of a two–carrier planetary gear train and kinematically equivalent planetary gear train, Acta Technica Corviniensis-Bulletin of Engineering, Vol. 16, No. 2, pp. 13-20, 2023.

[23] Felden, M. et al.: Electric vehicle drive trains: from the specification sheet to drivetrain concept: *14th International Power Electronics and Motion Control Conference*, 06-08.09.2010., Ohrid, North Macedonia, 10.1109/EPEPEMC.2010.5606531

[24] Rauth, S.S. and Samanta, B.: Comparative Analysis of IM / BLDC / PMSM Drives for Electric Vehicle Traction Applications Using ANN-Based FOC, 17th India Council International Conference, 10-13.12.2020., New Delhi, India, 10.1109/INDICON 49873.2020.9342237.

[25] Paulovics, L., Rohde-Brandenburger, J. and Tóth-Nagy, C.: Timing Chain Wear Investigation Methods – Review, FME Transactions Vol. 50, pp. 461-472, 2022, 10.5937/fme2203461P.

[26] Merve, S.K.: The Use of Induction Motors in Electric Vehicles, in: El-Shahat, A. (ed.): *Induction Motors - Recent Advances, New Perspectives and Applications*, IntechOpen Ltd., London, UK, 10.5772/intechopen.1000865.

[27] Hariharan, M., Kaup, V., Babu, H.: A Computa–tional Methodology for Synthesis of Epicyclic Gear Transmission system configurations with Multiple Planetary Gear Trains, FME Transactions, Vol. 50, No. 3, 2022., 10.5937/fme2203433H.

[28] Conwell, J. C., Johnson, G. E.: Experimental inves–tigation of link tension and roller sprocket impact forces in roller electric chain drives. Mechanism and Machine Theory, Vol. 31, No. 4, pp. 533-544, 1996.

[29] Davies, D. N. C., Gustafsson, K. G., Nordkvist, K.E., Owen, P. J.: Roller Chain as a Transfer Drive for the Automobile, Journal of Mechanical Design, Vol. 103, No. 1, pp. 19-28, 1981, 10.1115/1. 3254864

[30] Hanselman, D.: *Brushless Motors: Magnetic De–sign, Performance, and Control of Brushless Dc and Permanent Magnet Synchronous Motors*, E-Man Press LLC, Amsterdam, NY, USA, 2012.

[31] Liu, S.P., Wang, K.W. and Hayek, S.I.: Modelling and analysis of electric chain drive systems. J. Aco–ust. Soc. Am. Vol. 87, No. S1, pp. 136-139, 1990.

[32] Spicer, J.B., et al.: Effects of Frictional Loss on Bicycle Electric Chain Drive Efficiency. J. Mech. Design. Vol. 123, No. 4, pp. 598-605, 1999.

[33] Spicer, J.B. et al.: On the efficiency of bicycle electric chain drives. Tech. J. of the IHPVA, Vol. 50, pp. 3-9, 2000.

[34] Troedsson, I. and Vedmar, L.: A Method to Determine the Static Load Distribution in an electric chain drive, ASME J. Mech. Design, Vol. 121, No. 3, pp. 402-408, 1999.

NOMENCLATURE

I	Current (A)
P	Power (W)
T	Torque (Nm)
U	Voltage (V)
d	Diameter (m)
i	Transmission ratio (-)
m	Mass (kg)
n	Rotational speed (min^{-1} or s^{-1})
v	Linear velocity (ms^{-1})
z	Number of gear or sprocket teeth (-)
η	Efficiency (-)

List of indices

DL1	Driveline 1
DL2	Driveline 2
DL3	Driveline 3
E	Electrical
EM1	Electric motor EM1
EM2	Electric motor EM2
HG	High Gear
LG	Low Gear
M	Mechanical (power)
Mech	Mechanical (efficiency)
dc	Double Chain
em	Electric Motor
max	Maximum
nl	No Load
p	Peak
sc	Single Chain
ul	Under Load
1	Pinion or driving gear/sprocket
2	Wheel or driven gear/sprocket
11	Driving sprocket of Chain 1
12	Driven sprocket of Chain 1
21	Driving sprocket of Chain 2
22	Driven sprocket of Chain 2
T	Torque (Nm)
M	Mass (kg)
N	Rotational speed (min^{-1} or s^{-1})
v	Linear velocity (ms^{-1})

МЕТОДОЛОГИЈА ЗА ИЗБОР ЕЛЕКТРОМОТОРА ЗА ПОГОН МИНИ ТРАКТОРА ЗАСНОВАНА НА ЕФИКАСНОСТИ

А. Ибраим, Б. Абсадиков, С. Троха, К. Марковић, Ж. Врцан

Овај чланак се бави истраживањем и анализом електромотора и њихових усклађених система преноса у контексту свестраног електричног мини трактора дизајнираног за задатке као што су чишћење улица, одржавање урбаних паркова и транспорт малих терета. Примарни циљ истра–живања је да се процене снаге и слабости неколико комбинација електромотора и трансмисије дизај–нираних да задовоље специфичне оперативне зах–теве трактора. Како погонска линија мора да обезбеди значајан обртни момент уз одржавање оптималних услова рада и избегавање прегревања, спроведена је серија експеримената, који су пок–ривали различите конфигурације електромотора који раде у опсегу од 60В, са излазном снагом у распону од 1000 до 1500 вати и укључујући више–струке варијације мењача. Извршена је компа–ративна анализа како би се процениле предности и недостаци решења преноса са директним ланчаним погоном без диференцијала на крутој осовини, за разлику од заптивене јединице мотор-мјењач која садржи диференцијал и полуосовине. Резултати овог истраживања коришћени су за математичко упоре–ђивање решења погона, омогућавајући детекцију оптимално усклађених решења преноса и мотора.

Експерименти су такође обухватили идентифи–кацију енергетски ефикасних решења и оптималних параметара дизајна за електрични трактор који је изричито пројектован за континуирани рад дужи од 10 сати, са капацитетом терета већим од 500 кг, високом способношћу за маневрисање ван пута и веком трајања од преко 5000 сати. Динамички тестови спроведени током истраживања пружили су драгоцен увид у однос укупне енергетске ефикас–ности возила према варијацијама тежине и пренос–ног односа.