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Electric Vehicle Drivetrain Efficiency and the Multi-Speed Transmission Question

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Abstract: The availability of high-fidelity energy consumption estimates and the ability to evaluate drivetrain efficiency are crucial for effectively planning a large-scale transition to electric vehicles. For both new and retrofitted electric vehicles, a key question is the transmission type—single-speed or multi-speed—and the resulting impact on the vehicle's overall efficiency. This paper presents a comprehensive simulation-based methodology for evaluating the impact of transmission selection on vehicle efficiency using high-fidelity driving cycle data. The method can be used for new vehicles and retrofit applications where a transmission is already present. The efficiency of a single-speed reduction gearbox was compared to that of a five-speed multi-speed transmission in a retrofitted vehicle, of which the impact of the manual transmission on the vehicle dynamics and efficiency was examined. The manual transmission proved to be more efficient for a perfect gear-shifting strategy.

Keywords: electric vehicles; energy transition; vehicle conversion; motor efficiency; retrofit; transportation; drivetrain modeling

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1. Introduction

With the advent of electric mobility, a key question for new builds and retrofitting is whether a manual transmission (MT) or single-speed transmission would result in the most-efficient drivetrain. This paper answers that question using a drivetrain design of a retrofitted vehicle from Sub-Saharan Africa [1].

Global sectors are racing to reduce carbon emissions and avoid global temperatures rising by 1.5 °C before 2030 [2]. The transportation sector is responding to the global transportation transformation to electric vehicles (EVs). By 2035, no new internal combustion engine (ICE) vehicle is expected to be sold or registered in Europe [3,4].

However, developing countries are lagging. In 2022, Europe sold over 1.6 million battery electric vehicles, significantly more than the 500 EVs sold in South Africa [5]. As stated by Collett et al. [6], Sub-Saharan Africa must develop and implement innovative strategies to catalyze the EV transition. One of the methods utilized in this transition is the conversion of ICE vehicles to battery-powered EVs.

Therefore, as EV technologies continue to advance, there is an increasing need to deliver more-efficient electric drivetrains, which can serve as a retrofit solution to give used vehicles a second life. Retrofitting ICE vehicles as an objective results in a considerable reduction in carbon emissions, reduced environmental impacts, and the improved affordability of EV ownership. Given this context, an important avenue of investigation involves integrating a multi-speed transmission, in particular an MT, into EVs to optimize the vehicle dynamics and energy consumption.

The primary objective of this study was to assess the impact of an existing multi-speed transmission system on the efficiency of a retrofitted electric vehicle. Specifically, the focus was on comparing the powertrain efficiency of two distinct retrofitted electric drivetrain configurations: one equipped with the default five-speed MT and the other with a new single-speed reduction gearbox.

We utilized high-resolution tracking data obtained from an ICE vehicle to evaluate the energy consumption estimates (in kWh/km) for these two proposed retrofitted electric drivetrains.

These results will inform about the viability and advantages of incorporating a multi-speed transmission in retrofitting electric vehicles.

The integration of a multi-speed transmission in EVs represents a crucial research area, given the potential benefits. By allowing the EM to operate at the most-efficient points across a broader range of speeds, an MT can lead to optimized energy consumption and increased driving range. However, maintenance, mechanical inefficiency, and complexity must be accounted for, especially when considering using old MTs from the original ICE vehicle for the retrofit case. The insights gained from this study hold the potential to significantly influence the design and deployment of electric drivetrains in general, thus contributing to the ongoing transition to electric mobility beyond retrofitting.

To ensure a fair comparison, we used an electric drivetrain simulation that takes the required electric motor (EM) torque and speed from the driving cycle and combines it with a motor efficiency map to calculate the electric drivetrain efficiency [7]. This approach identifies potential gains in efficiency and performance that may arise from leveraging an MT's gear ratios.

As a use case, the driving cycle and characteristics of a Toyota-manufactured Hiace Ses'fikile minibus [8] were used to design and simulate the different electric drivetrain scenarios. This vehicle was chosen explicitly since it serves as the preferred choice of transport for most of South Africa's public transportation sector. Although extensive research has been conducted on improving EV efficiency through control strategies and technologies, this paper specifically addresses whether the original manual transmission of an ICE vehicle should be retained when converting it to electric in a Sub-Saharan use case.

The remainder of this paper comprises a comprehensive review of the literature on various aspects of electric vehicle drivetrain efficiency, explicitly emphasizing the influence of MTs. Our research methodology leverages driving cycle data and diverse electric drivetrain configurations to simulate powertrain efficiencies. These simulated efficiencies were subsequently used to calculate the overall energy consumption of the retrofitted electric vehicle across an entire driving cycle. We employed EV fleet sim as our simulation software to perform these simulations, as documented in [9]. The powertrain efficiency and energy consumption analysis aimed to elucidate the potential benefits and limitations of integrating an MT into retrofitted electric drivetrains.

2. Literature Review

A vehicle's overall operating efficiency depends on the powertrain's efficiency and sub-components. However, these efficiencies also depend on the states where the powertrain is operated during the vehicle's normal operation while it performs its driving cycles.

For example, the torque is affected by the load and rotational speed in revolutions per minute (rpm). From an integrated system perspective, the operational conditions are brought about by how the vehicle is driven, captured by the driving cycles.

To establish the effect an MT can have on the powertrain's efficiency as a function of the operational conditions, without considering the driving cycles, we conducted a detailed literature survey of the factors that affect the efficiency of a vehicle's powertrain. The vehicle's applicable driving cycles and specific use cases are addressed separately in Section 3.

2.1. Topology

A powertrain's individual components, consisting of the propulsion unit, transmission, and drivetrain, are shown in Figure 1. Although the transmission is often considered part of the drivetrain, it was analyzed separately in this paper to assess vehicle efficiency for powertrains with and without a multi-speed transmission.

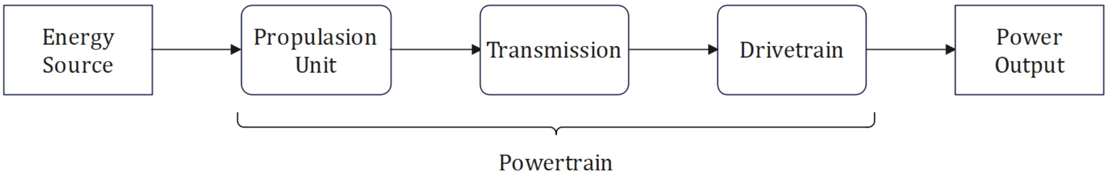


Figure 1. General flow diagram of vehicle powertrain components, specifically the propulsion unit, transmission, and drivetrain.

2.2. Propulsion Unit Efficiency

In the context of a retrofit, assessing the difference between the original and final power units in terms of operation and performance is essential. Accordingly, the ICE and the EM were analyzed here.

As a brief overview of ICEs, this type of heat engine converts chemical energy stored in a fuel into mechanical energy by burning the fuel inside the engine. The fuel is typically a hydrocarbon-based liquid fuel such as gasoline, diesel, or ethanol [10]. ICEs use a controlled explosion of fuel and air to drive pistons within the engine, producing rotational torque, which is transferred via other mechanical components, such as the gearbox, axial and differential, to produce a torque on the connected wheels that power the vehicle.

Figure 2 shows the characteristic curves at full load for an ICE (Figure 2a) and an EM (Figure 2b).

These characteristic curves are essential to understand a retrofit case, in which an EM replaces the ICE, and to ensure the original dynamic characteristics of the vehicle can be retained [11,12]. Figure 2b shows how the EM characteristics can be manipulated to improve powertrain efficiency with high initial constant torque and high rpm ranges, which can be manipulated by using multi-gear or single-gear transmissions. Thus, the wheel torque and speed and how they relate to the rpm and torque of the propulsion unit are crucial in this analysis.

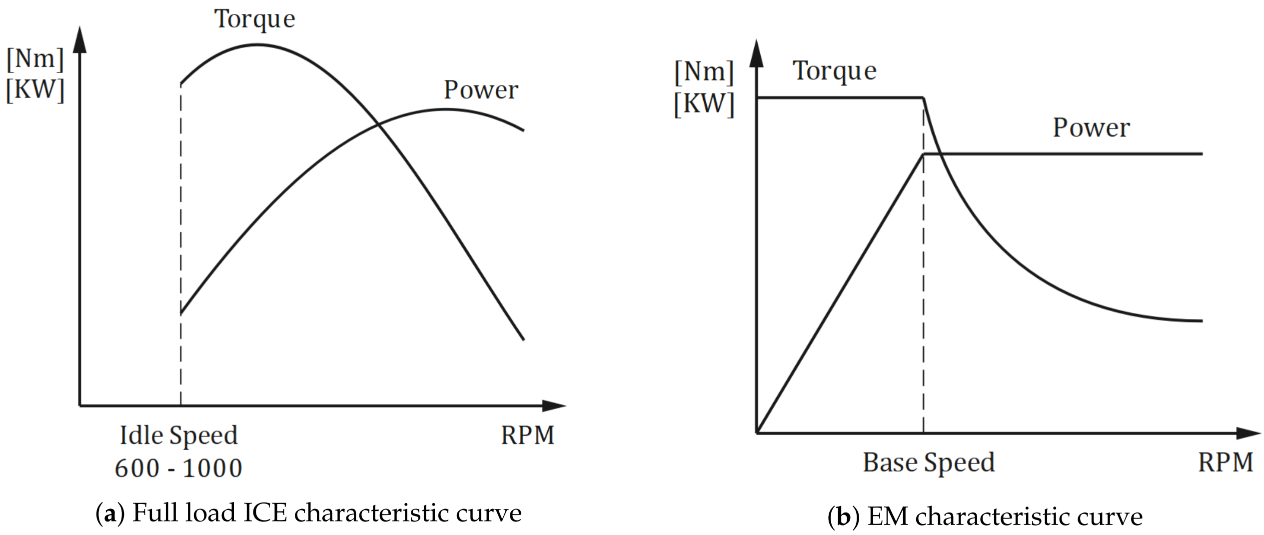


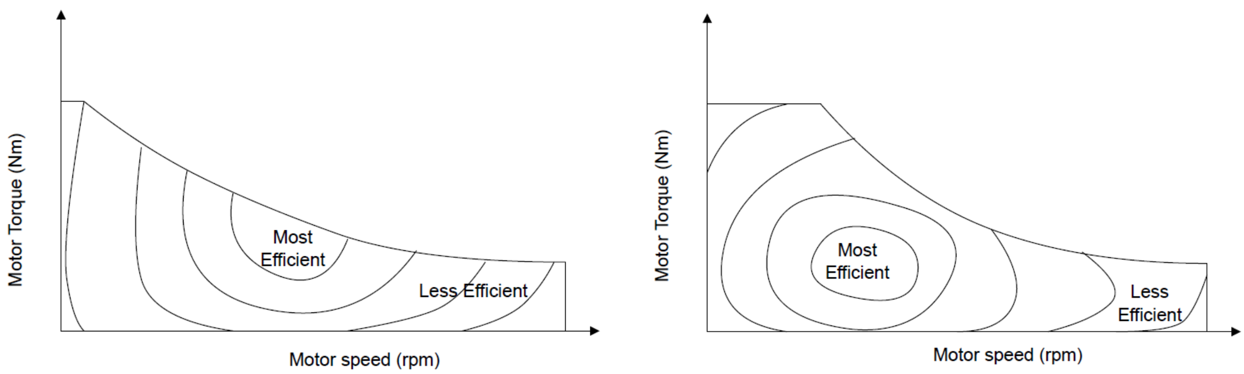
Figure 2. Comparison illustrated by looking at the characteristic curves of an ICE and permanent magnet EM. These figures were adapted from [13].

Figure 2 shows that the ICE needs to be running at an idle speed to produce torque. The EM, however, exhibits a maximum torque output, which increases from zero rpm to the base rpm, where the constant-power region starts. The average idle speed range for an ICE falls between 600 and 1000. This loosely translates to the fact that an ICE must be running at more than an estimated 20% of its rpm range to generate maximum torque.

In contrast, the EM can deliver maximum torque from 0 rpm, exhibiting superior torque characteristics compared to an ICE. In the constant torque region, the speed of the EM is adjusted by using a variable voltage control strategy until it reaches the base speed. As soon as the supply voltage from the inverter equals the rated EM voltage, the EM enters the constant-power region. At this point, the field-weakening region starts [14], which is determined by the physical limits of the current and voltage characteristics of an EM. For a permanent magnet synchronous motor, the magnetic field generated by the magnets, according to Faraday's law of electromagnetic induction, cuts through the stator windings, which induces a voltage [15]. This induced voltage increases as the speed of the EM rotor increases and is called electromotive force (back EMF). At base speed, the EM has technically reached its maximum rpm velocity at the rated voltage. However, to enable the EM to achieve higher rpm ranges, the EM is forced to go into its field-weakening region using the back EMF [14]. The back EMF opposes the applied voltage and, therefore, reduces the motor's current to maintain constant power [16]. Thus, the motor turns at a higher rpm, compensating for torque loss to maintain constant power. However, for vehicle applications, the decrease in torque is not a problem since high torque is not often required at high speeds.

However, the base speed of an EM is significantly higher than the speed at which the ICE experiences a decline in torque. This is due to the rpm range of an EM being broader than that of an ICE. Consequently, a single-speed gearbox is often used in EM powertrains, unlike conventional five-speed transmissions required for ICE, to generate comparable levels of rpm and torque across the range of vehicle speeds [13].

Electric vehicles typically use permanent magnet synchronous motors [17]. Figure 3 shows efficiency maps for two different types of permanent magnet synchronous motors, namely surface and interior mounted permanent magnet synchronous motors, which differ based on where the magnets are inserted in the rotor of the permanent magnet synchronous motor [17]. These maps relate the rotational speed of the motor and the torque due to the load on the motor to the operating efficiency of the motor under those conditions. To increase the efficiency of an electric vehicle, the motor needs to operate in the areas of high efficiency and avoid the areas of low efficiency.



(**a**) Surface mounted permanent magnet synchronous motor (**b**) Internal mounted permanent magnet synchronous motor

Figure 3. Efficiency map diagram comparison of a permanent magnet synchronous motorthat is surface mounted and one that is interior mounted.

The maps show that efficiency is particularly low at high rpm ranges. With a single-speed gearbox, a vehicle driving at high speeds will result in an EM operating at a higher rpm range to achieve the required vehicle speed.

It, therefore, stands to reason that using a single-speed gearbox results in inefficient conditions at high vehicle speeds.

Multi-speed transmission, on the other hand, can potentially enable the EM to operate in the higher efficiency region due to the different gear ratios, by operating the motor in the lower rpm range across the vehicle speed range. However, using an electric propulsion unit, it needs to be evaluated if the expected increase in motor efficiency caused by multi-speed transmission overrules the mechanical inefficiency added to the powertrain by the multi-speed transmission. This question was evaluated in the paper and compared to a conventional electric powertrain with only a single-speed reduction gearbox included in the powertrain.

Other Considerations

When considering retrofitting, the weight of the EM becomes a pivotal factor as the advantage stems from the replacement of the ICE with an EM in a retrofitting case. EMs can range from 20 kg to 50 kg, as observed in EVs like the Bosch smg180 [18]. This variability in weight offers an enticing opportunity to replace a portion of this mass with a more-desirable battery pack.

This substitution can keep the overall weight of the retrofitted electric vehicle within the gross vehicle mass (GVM) limit, which is an essential requirement for the homologation process. Therefore, choosing a high-energy-density battery pack and designing a lightweight electric powertrain system that satisfies the vehicle's performance requirements can assist in keeping the overall weight of a retrofitted electric vehicle within the GVM limit.

The weight limit is critical when integrating a transmission system into the propulsion efficiency considerations. While the additional weight from a multi-speed transmission can enhance the overall efficiency of the propulsion unit, it must be balanced against the vehicle's weight constraints, as it can potentially reduce the vehicle's overall efficiency.

2.3. Transmission Efficiency

In retrofitting scenarios, replacing the conventional transmission with a single-speed planetary gearbox (reduction gearbox) is common practice, since it provides several advantages. Firstly, it is relatively simple to implement and offers constant acceleration control. Additionally, it results in cost savings by eliminating the operational expenses associated with conventional transmission, such as maintenance costs, etc. Moreover, removing the conventional transmission from the powertrain reduces the vehicle's overall weight, allowing additional weight to be allocated to meet other requirements, such as larger battery capacity and homologation strategies [19]. However, given the efficiency improvements of using multi-speed transmissions, an open question is whether the transmission should be left intact.

Presently, the typical multi-speed transmission configurations used in electric vehicles (EVs) include clutchless automated MTs (CLAMTs), dual-motor multi-speed electric vehicle transmissions, continuously variable transmissions (CVTs) [20], inverse automated MTs (I-AMTs), dual-clutch transmissions (DCT) [21], and planetary transmissions, all of which are derived mainly from traditional transmission designs initially intended for ICE vehicles [22].

The transmission topologies mentioned above primarily aim to eliminate the use of clutches and torque converters due to the efficiency losses resulting from friction between the EM and transmission caused by clutches and the hydrodynamic losses of torque converters [23,24]. Additionally, torque converters require pre-revving to a specific rpm, leading to power dissipation in low-rpm conditions. These topologies also aim to provide seamless gear shifting by utilizing dual-clutch and synchronous systems to achieve optimal shifting sequences [25]. These specialized multi-speed transmissions are used in new electric vehicles designed for the specific transmission in use, such as the Porsche Taycan series and Audi E-Tron, which utilize specially designed automatic transmissions for seamless gear shifting, which increase the performance and efficiency of the vehicles [26,27].

However, using a new multi-speed transmission in retrofitting cases may not be viable due to the complexity of implementation and increased cost [28]. In retrofitting, the original transmission, designed for the ICE vehicle, must be adopted for use in the new electric powertrain. Most ICEVs primarily use automatic MTs (AMTs) and MTs.

Based on the information provided, using conventional transmissions with clutches or torque converters in electric powertrains appears unnecessary as it would decrease the powertrain's efficiency. However, using a single-speed gearbox with an EM limits the manipulation of the powertrain speed and torque output. Therefore, the EM needs to operate across the entire rpm range for the full range of vehicle speed, leading to high motor inefficiencies and a decreased motor lifespan.

Integrating a multi-speed gearbox can improve energy efficiency by optimizing the EM/inverter operating points during a given driving cycle. This is especially important because the EM and inverter efficiency vary significantly with torque and speed. Figure 4 illustrates the torque curve of a powertrain, with point "A" indicating the knee point on the original torque curve. At point "B", the benefits of a higher gear ratio (at lower gears) are highlighted, demonstrating the increase in torque available at a lower rpm. Specifically, the increased torque output gives the vehicle greater power to conquer steep inclines and tow heavier loads with increased ease and efficiency. Moreover, point "C" illustrates that the constant torque region is available for a wider rpm range for higher gears with smaller gear ratios than that of the original torque curve, thereby providing the vehicle with more torque access at higher speeds, such as when overtaking. Therefore, having multiple gear ratios available can enhance powertrain efficiency by manipulating the torque–speed curve to achieve optimal motor operating conditions based on the efficiency map, as shown in Figure 3. The increase in powertrain efficiency can result in vehicle range (km) and consumption (Wh/km) benefits [29].

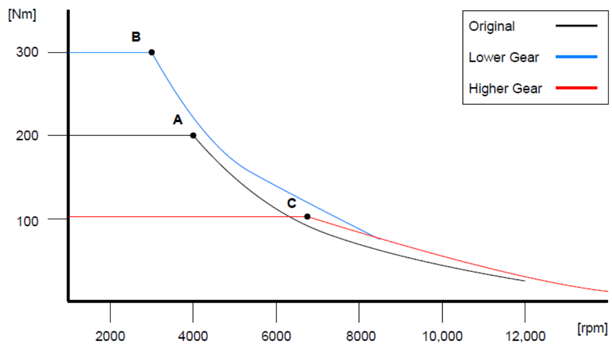


Figure 4. Torque vs. rpm curve for electric powertrain illustrating the knee point movement by using different gear ratios compared to the original powertrain curve with the EM.

2.3.1. Manual Transmission Efficiency and Losses

To accurately predict the overall efficiency of the powertrain in a retrofit scenario, it is necessary to determine the mechanical efficiency of the MT. This can be achieved through a detailed measurement or simulation using a dynamometer [30]. Alternatively, empirical data can be used to estimate the mechanical efficiency based on the gear ratio and load condition. In this paper, we retrieved the mechanical efficiency of an MT based on the literature. It is important to note that the mechanical efficiency of the MT is influenced by several primary losses, including frictional losses, due to the meshing of gears [31]. Gear losses can include frictional-load-dependent losses and load-independent churning and squeezing losses. The load-independent gearing losses are due to splash lubrication. Furthermore, bearings and seals also contribute to load-dependent losses [32].

The efficiency of an MT ranges from 92 to 97% depending on the load and speed input into the gearbox [19]. In this use case, the simulation will assume the worst-case efficiency since it is a retrofitted vehicle, and the transmissions will be somewhat worn down. Therefore, we accepted the MT efficiency, $\eta_{transmission}$, as 0.92. This mechanical efficiency of the MT was incorporated into the motor simulation model proposed in this study.

2.3.2. Manual Transmission Considerations

The first consideration in keeping the original MT in the retrofit powertrain is the added weight in the system. The weight of the retrofitted vehicle may not exceed the GVM of the original vehicle so that the homologation requirements set by the National Regulator for Compulsory Specifications (NRCS) [33] are adhered to. Therefore, keeping the conventional transmission leaves less additional weight to add electric components, especially a larger battery pack size. To determine the weight effect of the original transmission, the components being removed from the vehicle are weighed, and the gearbox is weighed in comparison to determine the weight efficiency. In general, Equation (1) can also be used to calculate a weight estimation of an MT [32]:

$$m_{\text{gearbox}}(\text{kg}) = 0.199 \cdot (i_{\text{G,max}} \cdot T_{\text{in}})^{0.669} \cdot Z^{0.334} \tag{1}$$

where $i_{\text{G,max}}$ is the maximum gear ratio (dimensionless), T_{in} is the input torque (Nm), and Z is the number of teeth on the gears (dimensionless).

Another important consideration is clutch losses. When the EM is disconnected from the load to be able to shift gears, the rotational speed of the EM output shaft and the MT input shaft are out of sync when reconnecting. The difference in angular velocities causes the clutch to slip when reconnecting until the angular velocities are equal again [34]. The power loss is due to the heat dissipation of the clutch. This power loss should be added to the EM and subtracted from the regenerative power. It is important to note that more power will be lost when the EM is accelerated by shifting to lower gears since the lower gear has a higher gear ratio. Therefore, the EM has to accelerate to keep vehicle velocity constant at that specific load. However, in this paper, we assumed constant driver torque demand, which allowed us to disregard the clutch losses in the proposed model.

2.3.3. Single-Speed Planetary Gearbox

In retrofitting scenarios, a reduction gearbox serves the crucial purpose of preserving torque and speed conditions within the drivetrain, much like those conditions output by an ICE in the original vehicle. One of the most-typical reduction gearboxes used in electric drivetrains is the straight-toothed single-stage planetary gearbox. The typical efficiency value of a planetary gearbox is approximately 0.97 [35]. This means that approximately 97% of the input power is transmitted to the output side, while the remaining 3% is lost as heat or friction within the gearbox.

Electric motors can rotate up to three-times faster than the original ICE, necessitating a reduction gearbox to align with the drivetrain's speed and torque specifications. This is crucial because drivetrain components like the differential gearbox and propeller shafts are engineered for specific load conditions. Without a reduction gearbox, the direct connection of an EM to these components could result in severe damage and failure due to the high motor speeds.

3. Methodology

This methodology uses a simulation to show whether an electric vehicle powertrain is less or more efficient with or without an MT. Firstly, it integrates the torque and speed requirements for an EM during a specific driving cycle. This simulation establishes a correlation between these requirements and the efficiency map of the selected EM [7]. As a result, a powertrain efficiency value is assigned to the motor for each data point in the driving cycle. Subsequently, an overall powertrain efficiency value is attributed to each data point, and this information is then processed with the 'EV fleet sim' software [9]. By employing software ('EV fleet sim'), the power consumption of both powertrains, with and without the MT, can be determined in terms of kilowatt-hours per kilometer (kWh/km).

3.1. Driving Cycle

The use case for this research was demonstrated on the Toyota Hiace Ses'fikile [1], which is a paratransit vehicle commonly used in Sub-Saharan Africa, shown in Figure 5.

To simulate the powertrain of this vehicle, this paper used high-resolution data collected through GPS tracking data gathered from taxis traveling in the area around Stellenbosch, South Africa [36]. From these data points, valuable insights were obtained regarding urban and inter-urban travel scenarios, allowing for a comprehensive analysis of the powertrain efficiency of the Toyota Hiace Ses'fikile regarding energy consumption (measured in kWh/km). While the data used in this method are specific to the Toyota Hiace Ses'fikile, the proposed methodology can also be applied to other vehicle data.

Figure 5. Toyota Hiace H200 Ses'fikile, commonly used paratransit vehicle in Sub-Saharan Africa [8].

The first step in determining the torque requirements for the EM is to filter the GPS tracking data to consider samples with positive acceleration exclusively. With the vehicle exposed to positive acceleration, it experiences either a positive net force when going downhill, as an example, or a negative net force when the total resistive force, acting on the taxi, is predominantly opposing the positive acceleration force from the propulsion unit. Given the high sample frequency, the simulation assumed that any net positive force in consecutive samples is due to the positive propulsion of the EM. Using the above-explained criteria ensures that the efficiency calculations are based on maintaining the vehicle dynamics. Negative propulsion occurs during regenerative braking, which is considered by assigning efficiency values to the inverter and battery pack of the selected powertrain. Therefore, all velocity and acceleration samples indicated in Figure 6 are assigned a motor efficiency value, which is used to determine the overall propulsion efficiency, η_{prop}, for each sample in the driving cycle data.

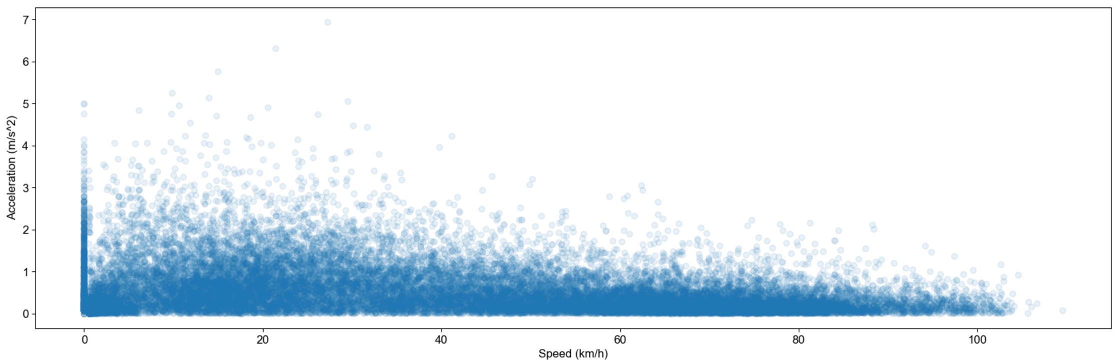


Figure 6. Acceleration versus velocity point for each sample, where $a[n] > 0$ m/s^2 and the net force is positive; clear grouping is seen at 0 km/h and at the legal urban speed limit of 60 km/h and less obvious groupings at 30 km/h and at the intercity limit of 100 km/h.

3.2. Simulation

Two primary powertrains for the retrofit were investigated to compare the efficiencies between an MT and not an MT. It is important to note that the single-speed gearbox is kept in both powertrains to accommodate the MT design limitations. In the first powertrain, shown in Figure 7a, the conventional powertrain of the ICEV is replaced with a battery pack and an EM while still containing the conventional transmission in combination with the single-speed gearbox. In the second powertrain, shown in Figure 7b, the MT is removed, and a single-speed gearbox is kept in the powertrain alone. Comparing the powertrain efficiency values of these two powertrains answers whether a conventional gearbox improves efficiency in the retrofitted vehicle. The efficiency of the powertrain is the ratio of the output power vs. the input power. The power supplied to the powertrain is sourced from the battery, while the output power is transmitted to the wheels. The original MT was designed for an rpm range between 3000 and 5000. Therefore, the single-speed gearbox allows the MT to be connected safely to the EM while operating up to 12,800 rpm.

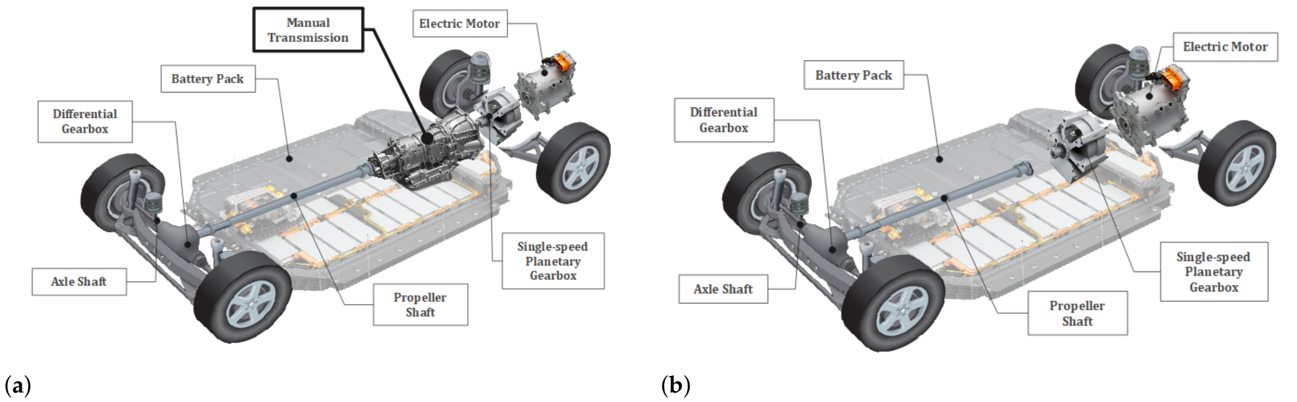


Figure 7. (**a**) Electric powertrain including the conventional manual transmissionand (**b**) electric powertrain with single-speed planetary gearbox.

From the driving cycle data above, the aim was to replicate the ICE vehicle dynamics recorded in the high-fidelity (HF) tracking data. A reverse-engineering methodology was implemented in this paper to assess the powertrain efficiency of the retrofit vehicle for each of those recorded movements in both powertrain scenarios. Figure 8 shows the proposed method's flow diagrams for both powertrains.

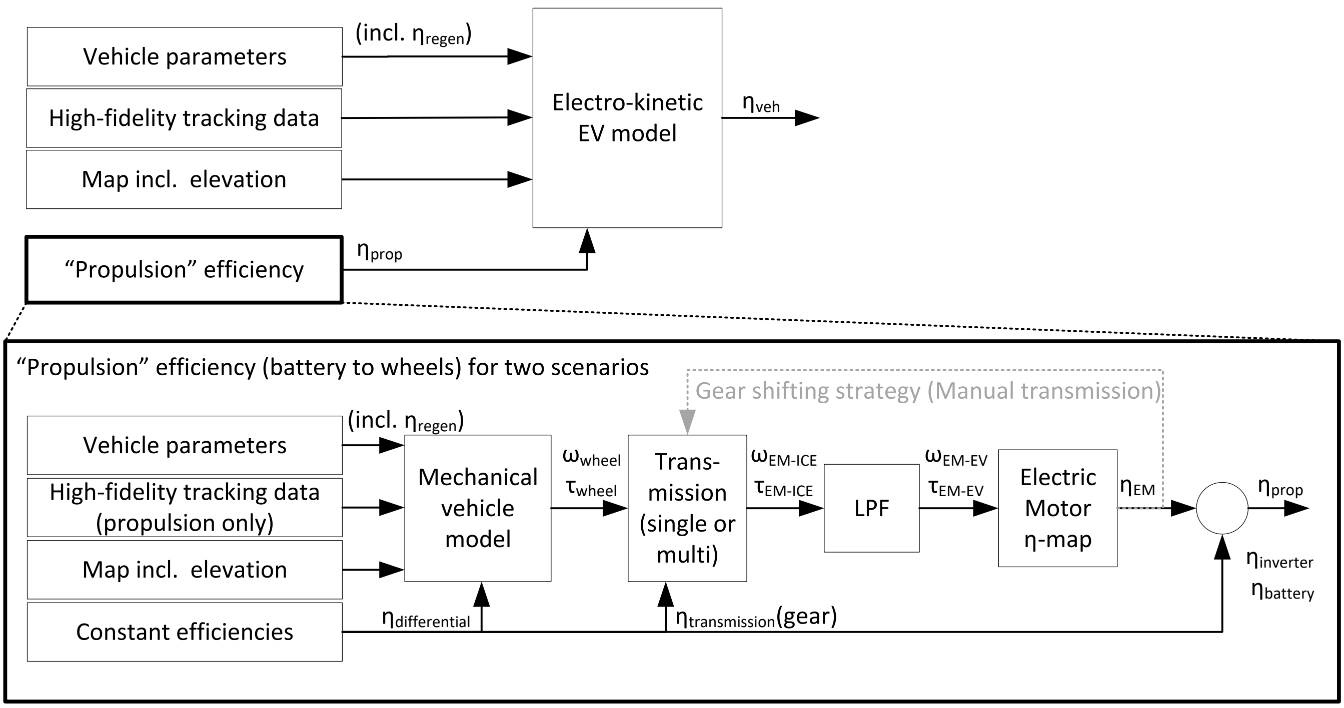


Figure 8. Methodology flow diagram for calculating the propulsion efficiency, η_{prop} for the two scenarios—with and without the manual transmission. In the existing work, η_{prop} was assumed constant. LPF refers to the low-pass filter that converts the ICE driving cycle to a viable EV driving cycle.

From the flow diagrams, the two main models used in Figure 8 are the electric motor model, indicated on the diagrams as 'EM-model', which refers to the powertrain efficiency model built by Lacock et al. [7], and the 'Electro-kinetic EV model', which refers to the simulation developed by Abraham et al. [37], in which the propulsion efficiency, η_{prop}, was assumed to be constant.

3.3. Shifting Strategy

In evaluating the impact of the MT on efficiency, the model, shown in Figure 8, incorporates a shifting strategy designed to assign the most-efficient gear based on a threshold of data points. This shifting strategy is an integral part of evaluating the efficiency of the MT powertrain.

The model calculates the motor efficiency for each gear scenario to identify the optimal gear across the step-sized data points. This process involves the use of the method presented by Lacock et al. [7], presented in Figure 9, which enables the determination of the gear efficiencies and guides the shifting strategy to enhance overall efficiency.

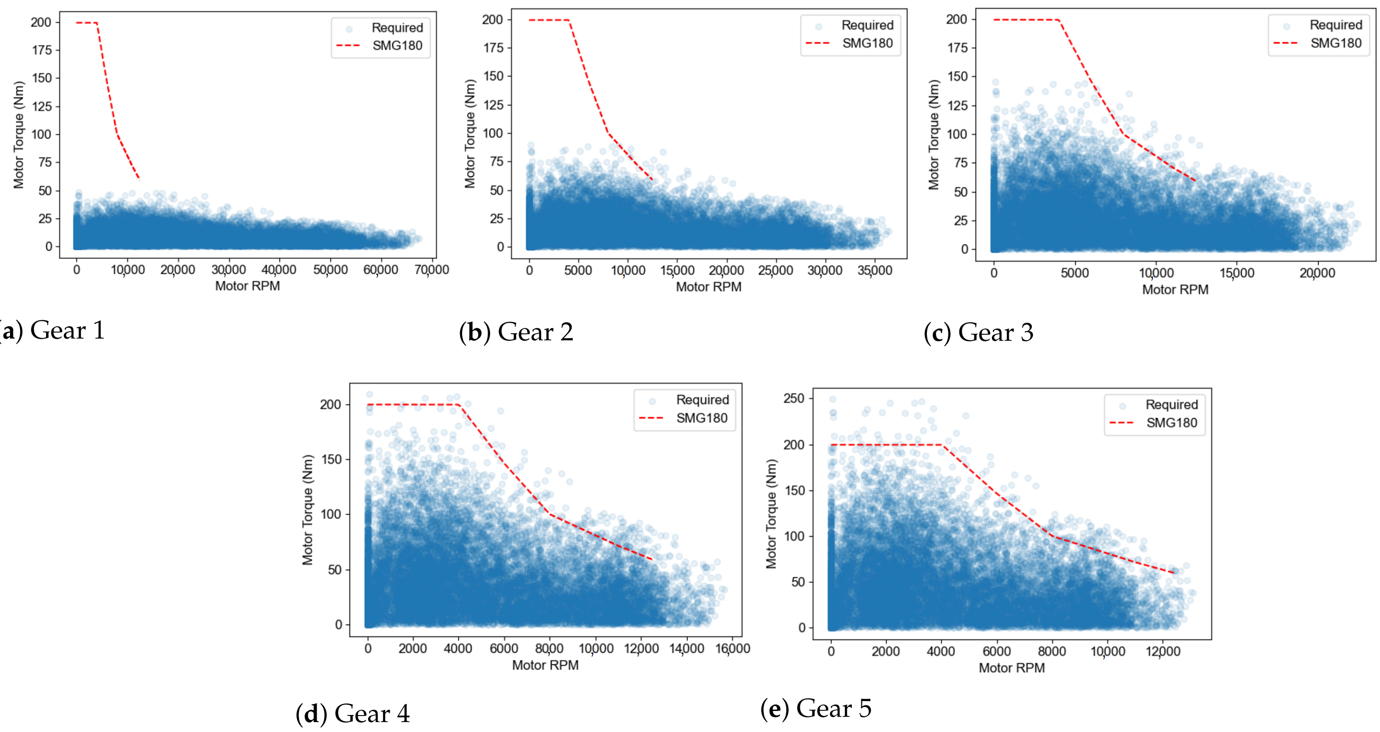


Figure 9. Required EM torque versus speed for all data points for each gear overlayed with the maximum torque and speed output curve of the Bosch SMG180 EM [18].

The model subsequently assesses and assigns gears to meet each data point's speed and torque requirements. This meticulous evaluation ensures that each data point is aligned with the gears capable of fulfilling its specific demands. This is illustrated in Figure 10, where the maximum speed of the vehicle is shown for each gear within which the torque requirements of the data points are met.

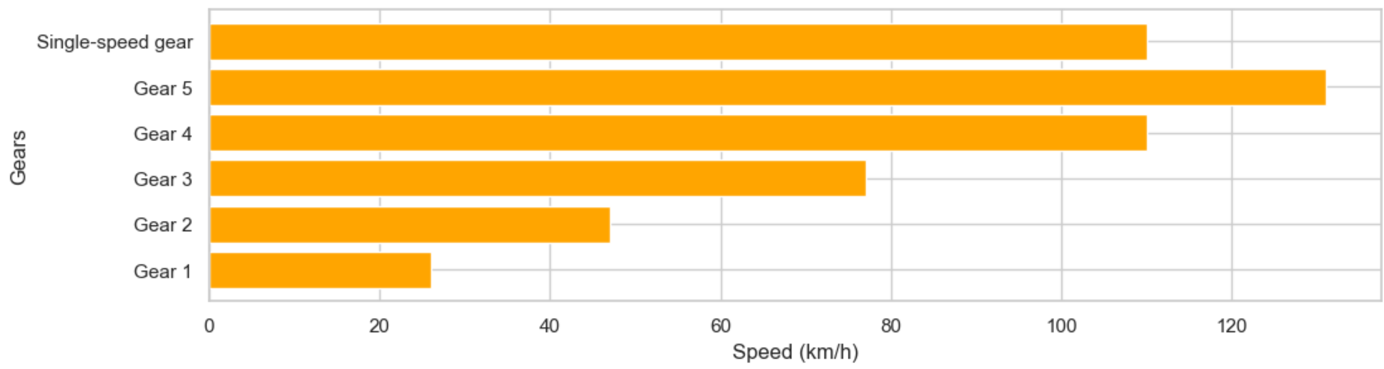


Figure 10. The maximum vehicle speed that can be achieved for each gear in which the electric powertrain meets the torque required.

The shifting strategy takes two inputs: the step size and the efficiency threshold. The step size represents the time interval between each data point, which is one second. The shifting strategy aims to find the optimal shifting schedule and assigns the corresponding efficiency value based on the gear indicated in the shifting schedule.

The shifting strategy calculates the maximum average efficiency for step data points between each gear. The gear with the highest average efficiency is logged for each step data point. The simulation then checks if the maximum average efficiency of the upcoming data point, which is n-step intervals away, is higher than the current average efficiency plus the efficiency threshold. If the criteria are met, the gear at which the criteria are met is used to assign a single motor efficiency value for all the data points in between. If the set of criteria is not met, the efficiency of the current data point is set to the efficiency corresponding to the current gear.

In this article, we assumed a step size of 10 s, and an efficiency threshold of 1% is shown in Figure 11, illustrating the optimal shifting schedule for motor efficiency. The step time was chosen based on the most-realistic time a driver would spend between gear shifts. From the simulation for this use case, the driver must shift 1493 times to achieve an optimal shifting strategy for the most-efficient motor operation over the driving cycle.

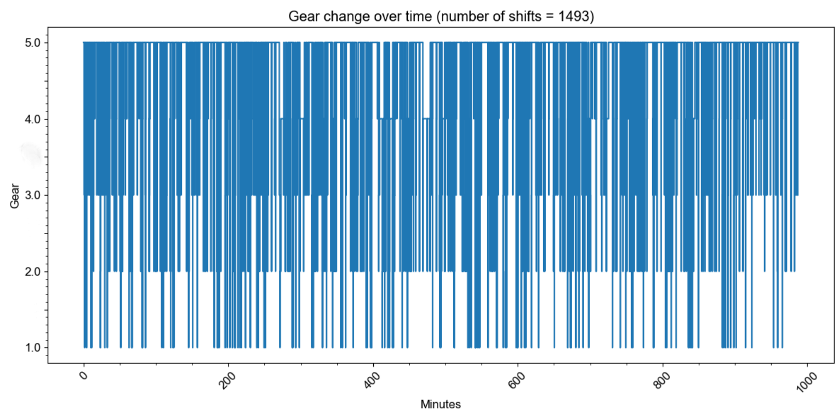
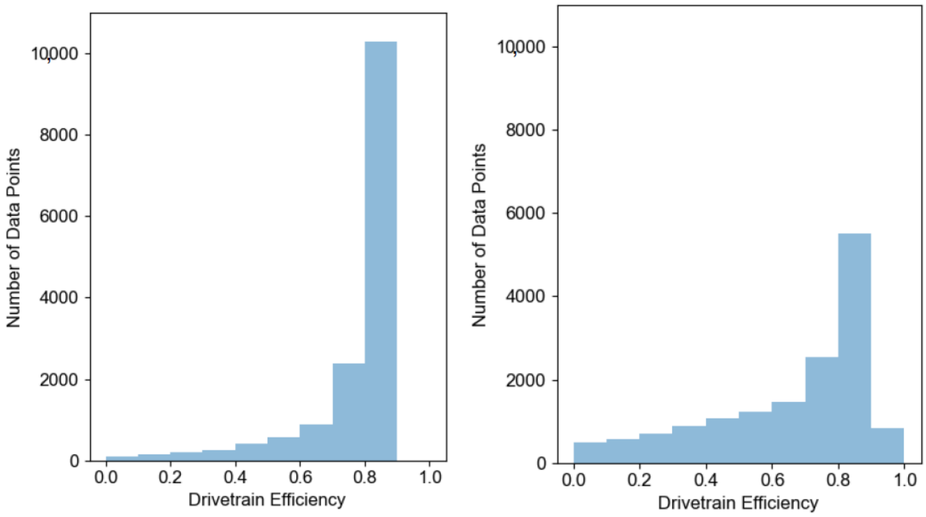


Figure 11. Optimal shifting schedule for 10 s time step and efficiency threshold of 1%.

4. Results

Figure 12 shows both powertrains' total drivetrain efficiency distribution. These graphs show that, for the powertrain with the MT, the data points are less distributed across the efficiency map. Therefore, we see a higher distribution of data points at a higher mean efficiency value than that for the powertrain without the MT. In Figure 12a, we observe a skewness coefficient of −2.56%, while for Figure 12b, we note a less-pronounced skewness coefficient of −1.35%. The higher percentage skewness is of particular significance as it shows higher efficiency with an MT than without. Upon examining the mean of the distribution, we observed that the powertrain with an MT demonstrated a 78% efficiency. However, a 73% mean efficiency was achieved for the powertrain without the MT. This proves that the MT with an optimal shifting strategy allows the EM to operate in more-efficient conditions than without using an MT.

Importantly, this distribution solely demonstrated the powertrain's performance during positive acceleration and positive net force (positive propulsion). However, further results need to be gathered on the total driving cycle in which negative propulsion also contributes to the vehicle's overall efficiency. The reason is that the MT enables the motor to operate under optimal conditions for positive propulsion. However, it is anticipated that the inherent inefficiencies of an MT can outweigh the advantages when the vehicle is experiencing negative propulsion. The reason is that, when the vehicle is decelerating, or power is being transferred to the battery through the generator, it also passes through the mechanical drivetrain, including the MT. Therefore, the accumulative energy consumption for both positive and negative propulsion was evaluated in both powertrains to determine the overall energy consumption for the vehicle across the entire driving cycle. The results are presented in Table 1.



(**a**) With MT (**b**) Without MT

Figure 12. Total drivetrain efficiency distribution for positive acceleration and positive net force data points in both scenarios—with manual transmission and without.

Table 1. Energy consumption comparison.

Powertrain	Energy Consumption (kWh/km)
With MT	0.67
Without MT	0.75

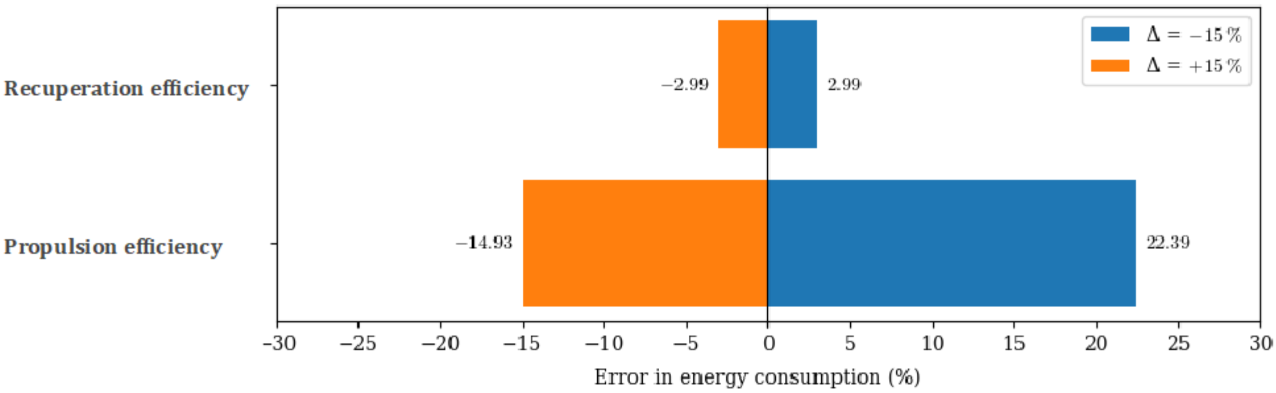
5. Analysis of Findings

5.1. Analysis

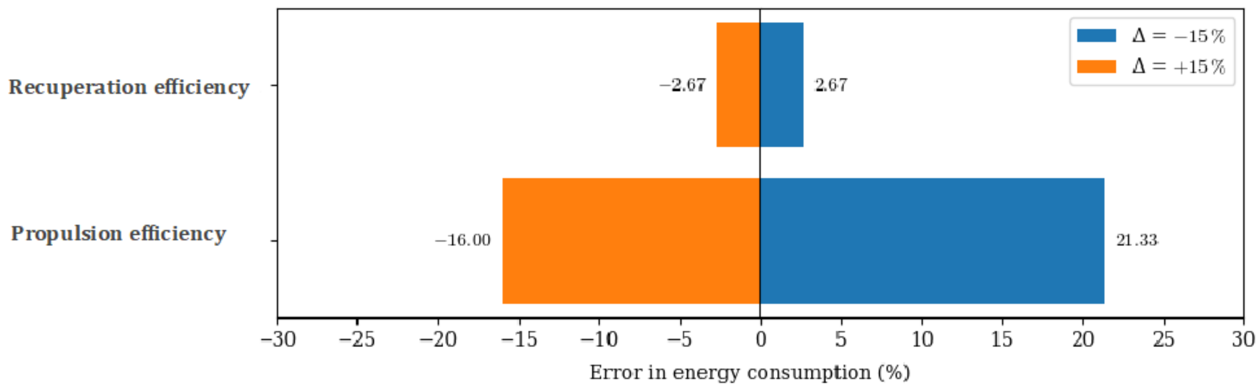
The analysis of Table 1 shows that the powertrain with an MT had higher overall powertrain efficiency compared to those without an MT, despite the mechanical inefficiency of the MT in the drivetrain. This is because optimizing the EM improved the powertrain efficiency. Although the MT caused some inefficiency during regeneration, its positive impact on the propulsion units outweighed the reduction in regeneration efficiency. Figure 13 presents an illustrative comparison of the total vehicle efficiency, considering variations in both the propulsion and regeneration efficiency values, each adjusted by ±15%. Alterations in propulsion efficiency resulted in substantially more fluctuations in the vehicle's energy consumption than equivalent recuperation efficiency changes.

Therefore, given a battery pack size of 53.760 kWh, the powertrain without the MT demonstrated a lower efficiency, equivalent to around 10 km less range than an MT, which had more extended range capabilities. This proves that having an option for more gear ratios can improve the overall powertrain efficiency and the vehicle's performance despite the mechanical inefficiency added to the electric drivetrain.

It is essential to consider that various unknowns may influence the energy consumption presented in this paper in the model used from [9]. As a result, the values provided in the paper serve as evidence to demonstrate that the MT indeed enhances the overall efficiency of the retrofit powertrain. Additionally, it is worth noting that the driving cycle data used were initially intended for an ICE vehicle (ICEV), and significant differences in driver behavior can arise when applying it to a retrofitted battery electric vehicle.



(**a**)



(**b**)

Figure 13. The percentage energy consumption change for a 15% change in the propulsion and recuperation efficiency (**a**) with an MT and (**b**) without an MT.

5.2. Other Manual Transmission Considerations

When considering the integration of an MT into electric vehicle drivetrains, several additional factors need to be considered. This section explores some of these considerations.

Using an MT in an electric vehicle can result in a harsher driving experience than vehicles equipped with a single-speed gearbox. MTs require the driver to manually engage gears, leading to abrupt shifts and a less-smooth acceleration profile. This harshness can impact passenger comfort, and the overall driving experience is the driving quality when using an MT in the powertrain. The three main factors that can be investigated to determine the driving quality of an MT in the drivetrain are the harshness, vibration, and noise of the powertrain. Harshness is due to the clutch slippages when the motor is reconnected to the transmission during gear shifts. Vibrations can emerge due to adding additional moving components into the system. Furthermore, while an electric motor (EM) typically generates minimal noise, including a transmission can introduce unwanted noise, which can be particularly undesirable within the context of a public transportation network [38]. Nonetheless, it is possible to mitigate this harshness by implementing a control strategy. This strategy involves the application of ramp-up control on torque changes per unit of time, accounting for factors such as clutch engagement during shifting changes to achieve smoother gear shifts. It is important to note, however, that this approach does increase the complexity of the controller.

MTs further introduce additional mechanical components and friction elements, increasing the drivetrain system's wear and tear. The clutch, in particular, is subjected to higher stress levels due to frequent engagements and disengagements. This can lead to increased maintenance requirements and potentially higher vehicle lifetime costs.

Electric vehicles are known for their instant torque delivery, allowing quick acceleration without a transmission. However, MTs may still offer advantages in terms of acceleration at higher traveling speeds. By enabling the driver to select the optimal gear ratio, MTs can enhance the vehicle's performance during high-speed manoeuvres or overtaking scenarios. It also increases the towing capacity capabilities by allowing higher torque ratio possibilities at lower speeds.

When implementing the original transmission of the vehicle in an electric conversion, it is essential to consider the physical condition of the transmission itself. Since the transmission is likely from a previously used ICE, it may already be worn and nearing the end of its expected lifetime. This means the transmission may require replacement sooner than anticipated, adding to the already high initial cost of the electric vehicle conversion.

Furthermore, MTs generally require more maintenance and are susceptible to potential repairs compared to electric drivetrain systems without a transmission. The clutch, gears, and other mechanical components of the MT can experience wear and may require more intermittent maintenance or repairs over time. These additional maintenance and repair costs should be considered when considering the integration of an MT in an electric vehicle.

A final consideration is adopting driver behavior ability when driving an electric vehicle with an MT. The driver would need to adapt to shift gears more optimally and ensure regenerative braking acts similarly to what it would have without MT. One approach to consider is adopting a strategy where the clutch is not engaged during deceleration, which differs from the practice in ICE vehicles. The driver would, however, not be able to determine when to shift gears, as shown by the shifting strategy. Hence, electronic methods must be implemented to provide the driver with indications regarding the most-suitable gear for a given situation.

Considering these factors, the decision to incorporate an MT in an electric vehicle should be carefully evaluated, weighing the potential benefits of performance and efficiency against the potential drawbacks related to the driving experience, maintenance, noise, complexity, and cost implications.

6. Conclusions

In conclusion, this paper aimed to address whether a manual transmission should be employed in converting an ICE to a battery electric vehicle. To achieve this, the study compared the operational principles of an ICE and an EM, emphasizing the potential enhancement of EM performance through access to various gear ratios, as reflected in its efficiency maps.

The investigation involved defining the drivetrain efficiency by analyzing the motor efficiency map for two scenarios: one using a single-speed reduction gearbox and the other incorporating a manual transmission. By evaluating the required torque data from the driving cycle of the Toyota Hiace Ses'fikile for both drivetrains, a shifting strategy was devised to optimize the drivetrain efficiency for the manual transmission scenario.

The result of the shifting model indicated that, when the manual transmission's gear ratios were utilized optimally throughout the driving cycle, the drivetrain's efficiency improved by 5% compared to the non-manual transmission scenario. Furthermore, the advantages of employing a manual transmission were demonstrated by the higher energy efficiency of the vehicle for both positive and negative propulsion throughout the entire driving cycle, even though the manual transmission introduced mechanical inefficiencies.

The findings of this article are valuable for stakeholders involved in the electrification process, including automotive manufacturers and transportation and charging infrastructure planners and developers. By providing simulation-based evidence, we aimed to provide valuable insights that can inform decision-making related to optimal drivetrain design and powertrain efficiency evaluation in electric vehicles.

Overall, this paper suggests that incorporating a manual transmission in the conversion of an ICE to a battery electric vehicle can lead to improved energy efficiency and optimized drivetrain performance during real-world driving conditions.

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