Multi-speed Gearboxes for Battery Electric Vehicles: Current Status and Future Trends

Fabricio A. Machado, *Student Member, IEEE*, Phillip J. Kollmeyer, *Member, IEEE,* Daniel G. Barroso, and Ali Emadi, *Fellow, IEEE*

Abstract In the last decade, the automotive industry has undergone a paradigm shift towards electrification. Electric vehicles have become increasingly popular, but so far, they have almost solely utilized single-ratio gearboxes. The use of multiple gear ratios has several potential benefits, including enabling the electric traction machine and inverter to operate in a more efficient region, increasing vehicle acceleration, gradeability, and top speed, and reducing overall traction system mass and volume. Performance vehicles, light to heavy-duty trucks, and buses may especially benefit from multi-speed gearboxes due to their high torque and power requirements. This paper covers the fundamentals of applying multi-speed gearboxes to EVs, the latest designs, and future trends. The efforts of both academia and industry in this field are covered. A range of topics are discussed, including gearbox topologies, gear ratio selection, gearbox losses, noise vibration and harshness, gearbox control, shift scheduling, and regenerative braking. Prior studies are presented showing that depending on the drive cycle, vehicle type, and gearbox configuration, drivetrain energy consumption may be reduced slightly or increased anywhere from a few percent to thirty percent when utilizing a multi-speed configuration. While multi-speed EV traction systems do show considerable promise, more investigation is needed to conclusively determine in what cases they can outperform highly optimized single-speed systems.

***Index Terms* — Battery electric vehicle, EV gearboxes, gearbox controlling, gear ratio design, multi-speed gearbox, shifting schedule**

I. Introduction[1]

THE automotive industry has been experiencing rapid change related to drivetrain electrification. The sales of battery electric vehicles (EV) have increased significantly in the last decade and accounted for 2.5% of the global market share in 2019 [1]. The International Energy Agency projects a worldwide growth of EV sales of 36% annually, reaching 245 million cumulative vehicles in 2030 – a more than 30 times increase from 2020 [2]. According to the Transportation Research Center at Argonne National Laboratory, the sales of light-duty electric drive vehicles in the United States more than doubled from 2017 to 2018, from 104,492 to 241,912 [3] (Fig. 1). The EV transmission market is, consequently, expected to grow as well, to US$17.6 billion in 2027, with a compound annual growth rate of 18.8% for the forecasted period [4].

EVs equipped with single-speed gearboxes are currently dominant in the market [5]. The single-speed architecture of EVs such as the Chevrolet Bolt and Chevrolet Spark are designed with the aim of achieving simplicity, low cost, efficiency, and adequate acceleration and top speed [6], [7]. A single-ratio gearbox has some limitations, though, as it cannot always ensure the operation of the electric traction machine (EM) and inverter in the optimum efficiency region [8]. With the expansion of the EV market, more broad segments of vehicles, such as minivans, vans, and light to heavy-duty trucks, will also undergo electrification [9], [10], [11]. Multi-speed gearboxes may be better suited to achieve the load, towing, off-road, and top speed needs for these vehicles.

The use of a multi-speed gearbox may increase the manufacturing cost of an EV and will require the implementation of a gearbox control [12] and shift strategy [13], [14]. The efficiency of a conventional multi-speed gearbox is also generally lower than a single-speed gearbox [15]. Nevertheless, researchers have shown that multi-speed gearboxes have the potential to reduce overall vehicle energy consumption, which could be translated to an extended driving range for a smaller battery pack, improved dynamic performance, and gradeability. Recent studies have demonstrated that multi-gear ratio systems could reduce energy consumption between 2 and 20% for a variety of drive cycles [13], [15], [16], [17] and increase drive wheel

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torque by 35% [18].

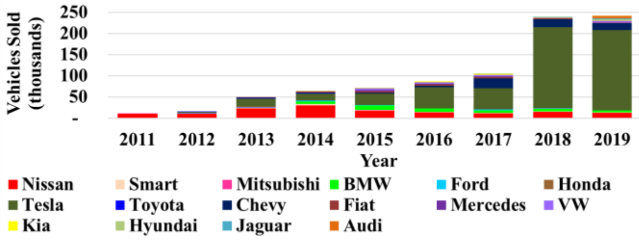

Fig. 1. Light-duty EVs sold in the United States from 2011 to 2019 per automaker brand [3].

The performance of a multi-speed gearbox for EVs is typically evaluated based on three primary quality metrics: dynamic performance, energy consumption, and driving comfort [19], [20], [21]. The most challenging of these to quantify is driving comfort, although some effort has been made to model this factor [22]. To improve comfort and reduce noise, vibration, and harshness (NVH), the speed and torque of the electric motor must be precisely controlled to avoid jerk during gear changes [8]. Moreover, the shift schedule must be defined to prevent shift hunting, i.e. excessive gear changing to maintain comfort and performance [23]. When designing a multi-speed gearbox, it is also necessary to consider the method for downshifting during deceleration to maximize regenerative braking energy capture, the ratio spread between gears, the impact of reduced overall gearbox efficiency compared to a single-gearbox system, and integrated powertrain co-design considering the electric machine, inverter, and battery.

This review paper covers the technical fundamentals of the application of multi-speed gearboxes to EVs, the latest proposed gearbox designs, research on multiple topics related to modelling, testing, and implementing multi-gear systems for EVs, and future trends. Thus, this paper aims to provide a comprehensive review of academia and industry's effort to improve EVs' energy efficiency and dynamic performance via multi-speed gearboxes. Gearbox and electric traction system design is a broad field; for more detail than is provided here, readers are referred to the following textbooks: [24] and [25] (transmissions), [26] and [27] (automotive engineering), [28] (automotive controls), and [29] (electric drivetrains).

The paper begins with an overview of gearbox types and their respective cost, mass, and other characteristics in Section II. Methods for selecting gear ratios, gearbox loss, and NVH are discussed in Section III. Shift control, scheduling, and mapping, and regenerative braking are covered in Section IV. Finally, in Section V the energy efficiency and performance benefits of a range of multi-speed gearbox EV drivetrains are presented.

II. Gearbox Topologies

A. *Gearbox Architectures*

Several existing gearbox topologies are suitable for EV applications. These topologies cover a range of vehicles, from small passenger cars to heavy-duty commercial trucks. Gearboxes can be categorized into five traditional groups: manual transmissions (MT), automated manual transmissions (AMT), dual-clutch transmissions (DCT), automatic transmissions (AT), and continuous variable transmissions (CVT). Researchers have also investigated inverse-automated manual transmissions (I-AMT), infinitely variable transmissions (IVT) [30], and magnetic gear transmissions (MGT) [31]. The different gearbox types are described in detail in this section, except for the AT, which is only suitable for internal combustion engine (ICE) vehicles due to its use of a torque converter [24].

The MT, AMT, I-AMT, and DCT utilize a combination of clutches and synchronizers to engage and disengage the different gear ratios. Clutches transmit torque via friction and, importantly, can transmit torque even when the speeds of the two shafts are different, allowing for torque to be transmitted to the wheels throughout the shifting process. Synchronizers transmit torque via a mechanical locking mechanism; a set of teeth on the synchronizer are inserted into the driven gear, locking the speed of the two together [24]. A frictional cone clutch is used to align speeds while the synchronizer teeth are engaged, but this cone clutch can only transmit a small amount of torque, preventing the synchronizer from engaging under load like a clutch.

Clutches are typically used to disconnect the engine or electric machine from the gearbox; then, synchronizers are used to select the gear while the gearbox is unloaded. DCTs utilize two clutches – a dog clutch (positive locking clutch), multi-plate clutch (friction clutch), or a combination of both systems [32] – and can shift under power by closing one clutch while opening the other. Alternatives to conventional friction-based cone clutch synchronizers are also being investigated for EVs, such as the harpoon shift synchronizer in [33], which reduces loss during gear shifting by not using a friction element for synchronization.

Manual Transmission (MT)

The classical gearbox topology is the MT, as shown in Fig. 2(a). The driver shift gears manually with a lever while engaging the master clutch, which disconnects the engine from the gearbox [25]. When the driver engages a gear with the shift lever, the synchronizer mechanically aligns the speed of the gears with the rotating differential, which drives the wheels. Some ICE-powered vehicles which have been converted to EVs utilize the stock MT [34] for simplicity. While MTs are reliable, low cost, and low maintenance [26], they are rarely, if ever used, in production EVs because the ride quality, system efficiency, and clutch life are strongly affected by how the driver operates the gearbox.

Automated Manual Transmission (AMT)

The AMT, as illustrated in Fig. 2(b), is a variant of the MT, where electrohydraulic or electromechanical actuators engage the synchronizer(s) and change gears [25]. For ICE vehicles, the AMT would include a clutch, but this is not necessary for EVs since motor speed and torque can be precisely controlled. The gear shifting is controlled automatically by a transmission control unit (TCU), as shown in Fig. 2(b). The motor torque is set to zero, the synchronizer is disengaged, the motor speed is adjusted for the new gear, and the synchronizer is re-engaged. Torque is interrupted during this process, preventing a completely smooth shifting of gears. By applying an eddy current torque bypass clutch, as proposed in [35], smooth shifting can be achieved, making the AMT more suitable for electrified traction systems. Although the AMT has never found extensive use in ICE-powered vehicles [24], it is a promising candidate for EV applications due to its low manufacturing and maintenance cost, simplicity, ease of implementation, and efficiency.

Inverse-Automated Manual Transmission (I-AMT)

An I-AMT is very similar to an AMT, except that it includes a clutch to connect the second gear rather than a synchronizer, as is shown in Fig. 2(c). The first gear is engaged or disengaged by the synchronizer, and power is blended in using the clutch. As proposed for EVs in [36], this novel layout reduces torque interruption during shifting by about 50% compared to a traditional AMT. With improved controls, it may be possible to fully compensate torque and realize seamless gear shifting [36].

Dual-clutch Transmission (DCT)

Aiming to combine the advantages of MT and AT without the torque interruption present in AMTs, the DCT was introduced in Porsche and Audi vehicles in 2003 [37]. The DCT, as shown in Fig. 2(d), has two shafts connected to the motor via independent clutches, one for odd gears and one for even gears. Smooth-shifting can be achieved by disengaging one clutch while engaging the other and controlling the clutches simultaneously [25].

The type of clutch used, wet or dry, can have a large impact on the DCT design and efficiency [24]. A wet clutch has oil on the clutch plates, providing a good medium for cooling but causing significant drag and fluid churning loss, while a dry clutch has no oil on the plates, reducing loss but making it difficult to remove heat [38].

Continuously Variable Transmission (CVT)

A CVT utilizes tapered discs and a belt or chain to enable the gear ratio to vary continually from the minimum to the maximum ratio, as shown in Fig. 2(e) [25]. Compared to a typical gearbox with fixed ratios, a CVT can keep the motor operating at its peak efficiency points for a much greater proportion of the time. There is significant power loss in CVTs due to friction between the belt or chain and the taper discs, which are moved together or apart to adjust the gear ratio [24]. Power is also required to apply pressure to the taper discs to hold them in place, and the chain or belt may slip under some circumstances, like starting from a stop for an ICE vehicle, causing further loss. All of these sources of loss lead to the CVT being the least efficient gearbox type. The smooth operation, lack of torque interruption, and ability to operate the traction machine at a wide range of speeds have been enough motivation though for many researchers to investigate CVTs for EV applications [13], [15], [16], [17].

Infinitely Variable Transmission (IVT)

The lowest gear ratio of a CVT can be reduced to zero or even negative by adding a fixed ratio and a planetary gearset, creating a transmission where the ratio of input to output speeds can be infinite [39]. The planetary gearset can be connected directly to the motor shaft for the series configuration (Fig. 2(g)) or to the output of the fixed ratio gearset for the parallel configuration (Fig. 2(f)). The range of gear ratios achievable with the IVT is a function of the CVT, fixed, and planetary gear ratios, as described in the kinematic equations for the gearbox [39]. The main appeal of the IVT is that the lower ratio can be zero, allowing an ICE to operate at idle without a clutch as would be required for the CVT [40]. Since electric machines can produce full torque at zero speed, there is no significant benefit of the IVT over the CVT for EV applications.

Magnetic Gear Transmission (MGT)

A magnetic gear transmits force via a magnetic field rather than through the meshing of physical gear teeth. Permanent magnets are used in place of teeth, and the ratio of magnetic pole pairs on the inner and outer rotors or planetary type gears determines the gear ratio, as illustrated in Fig. 2(h) and Fig. 2(i). Magnetic gears are appealing because they are contactless, require no lubrication, and have inherent overload protection. Magnetic gears utilize a large amount of magnets, though, 14.7 kg per prototype EV wheel motor in [41], which is cost-prohibitive. Their efficiency is also low, with about 2.5 kW of loss per wheel motor at 100 km/h in [41], which translates to only around 75% efficiency for highway driving and makes magnetic gear motors unappealing for EVs.

B. Gearbox Mass and Cost Assessment

Gearbox mass and manufacturing costs increase as more gears are added. To give insight into the impact of the number of gears on mass and cost, the gearbox design methodology proposed in [24] is used in this section. The gearbox mass ($m_{gearbox}$), for coaxial two-stage passenger and commercial vehicle MT gearboxes, in kg, is expressed by Equation (1).

$$m_{gearbox}(kg) = 0.199.\left(i_{G,max}.T_{in}\right)^{0.669} Z^{0.334} \quad (1)$$

where $i_{G,\,max}$ is the maximum gear ratio, T_{in} is input torque, and Z is the number of gears.

Similarly, [24] defines the Relative Gearbox Cost (RGC) of an MT gearbox as a function of the parameters T_{in}, $i_{G,max}$, and Z as defined in (2).

$$RGC = 0.0183.\left(i_{G,max}.T_{in}\right)^{0.512} Z^{0.256} \quad (2)$$

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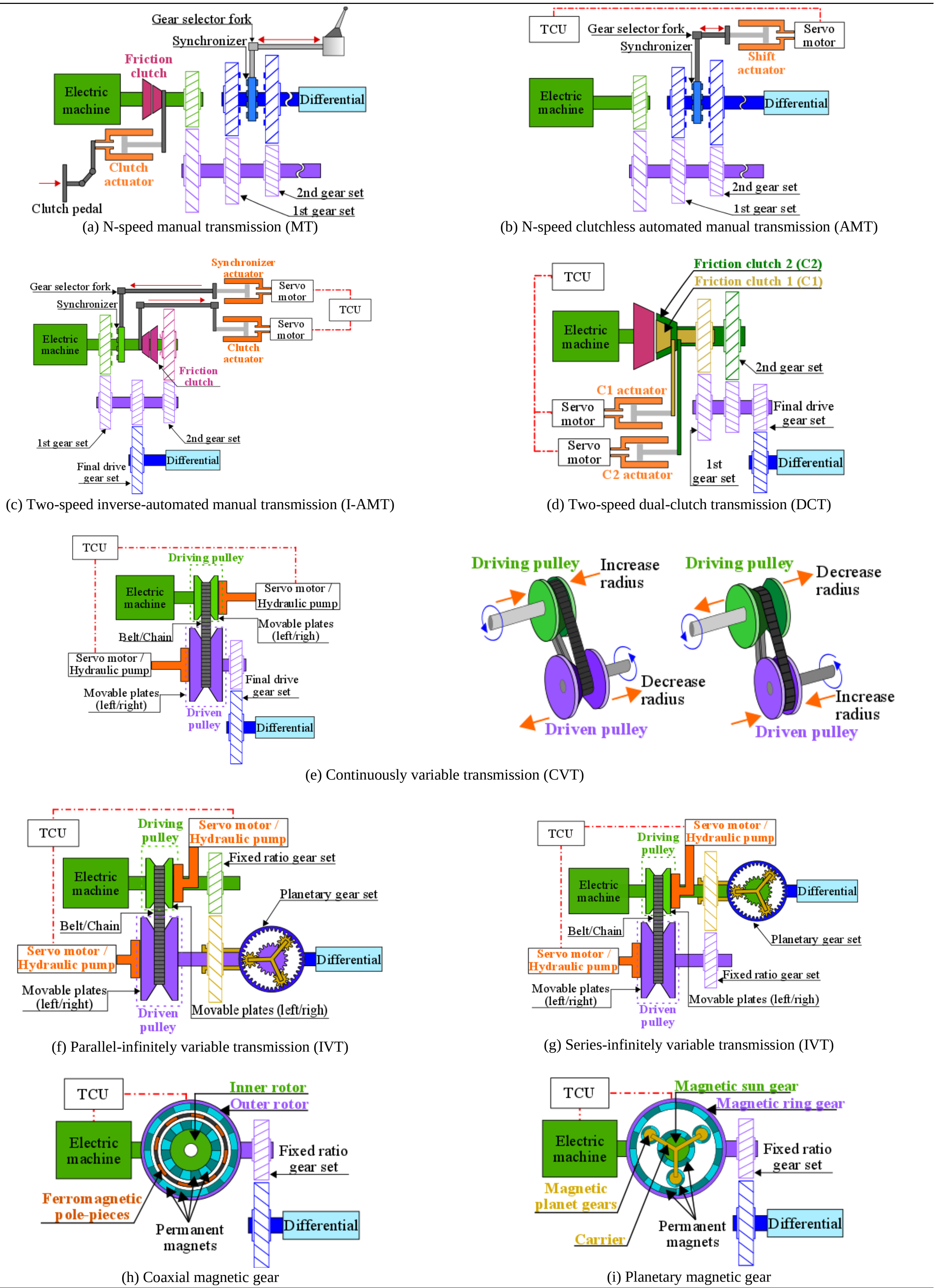

Fig. 2. Schematics of different gearbox topologies used for battery electric vehicles.

MTs, as the above equations refer to, are the cheapest and lightest gearbox type. The mass of other gearbox types in relation to MTs is defined as the relative mass/cost factor, R_f, and is stated in TABLE I for AMTs, DCTs, I-AMTs, CVTs, and IVTs as given in [24]. Because the cost is generally a function of the transmission mass [42], the cost and mass weighting factors are assumed to be identical. As MGTs are still at the research stage, there is insufficient data available to make a relative mass and cost comparison.

TABLE I
REFERENCE VALUES FOR THE RELATIVE MASS/COST FACTOR PER GEARBOX TYPE [24]

Gearbox Type	Relative Mass/Cost Factor (R_f)
Single-speed	1
MT	1
AMT	1.09
DCT	1.32
I-AMT	1.09 (same as AMT)
CVT	1.38
IVT	1.88*
MGT	N/A

*IVT transmission is considered to be 36% heavier than a CVT [30]

When the maximum gear ratio, $i_{G,max}$, and input torque, T_{in}, are held constant for different gearbox types, only the number of speeds and the gearbox type will differentiate the mass and cost. Therefore, to compare gearboxes with different speeds, normalized $m_{gearbox}$ and RGC are more appropriate, as expressed by (3) and (4), respectively,

$$m_{gearbox,\ normalized} = R_f \left({}^{Y}\!/_{X} \right)^{0.334} \quad (3)$$

$$RGC_{normalized} = R_f \left({}^{Y}\!/_{X} \right)^{0.256} \quad (4)$$

where Y is the number of gearbox speeds to be compared, and X is the number of speeds of the reference gearbox. To calculate the relative cost and mass of a CVT, it is considered a 6-speed gearbox as in reference [24].

C. Gearbox Topology Summary

TABLE II summarizes the types of gearbox topologies for battery EVs, the number of speeds, average efficiency (not including the differential), and the normalized mass and cost. The 4-speed MT has normalized mass and cost of one because it was chosen as the reference gearbox.

Although the gearbox topologies showcased in TABLE II were originally developed for classical ICE-propelled vehicles, they can also be used in EV applications with some considerations. Recent gearbox designs focused on EVs have greatly optimized gearbox size, improved integration of the differential, and significantly increased efficiency. For instance, Audi has designed a compact, high-power-density single-speed gearbox for the newly launched Audi e-Tron [43]. Also, modern state-of-the-art CVTs utilize compact, on-demand electric oil pumps (EOP) to activate hydraulic actuators to change the CVT speed ratio. This on-demand EOP considerably reduces CVT size and the energy demand, resulting in higher gearbox efficiency [44].

TABLE II
SUMMARY OF CHIEF GEARBOX TOPOLOGIES DEPLOYED IN BATTERY EVS. COST AND SPEED ARE NORMALIZED TO A 4-SPEED MT.

Gearbox Topology	Gearbox Type	# of Speeds	Average Efficiency*	Normalized Gearbox Mass	Normalized Gearbox Cost
Single-speed		1-speed	$\eta > 0.98$	0.63	0.70
	MGT	1-speed	$\eta < 0.94$[1]	N/A	N/A
Multi-speed	MT	2-speed	$0.92 < \eta < 0.97$[2]	0.79	0.84
		3-speed		0.91	0.93
		4-speed		**1**	**1**
	AMT	2-speed	$0.92 < \eta < 0.97$[2]	0.86	0.91
		3-speed		0.99	1.01
		4-speed		1.09	1.09
	DCT	2-speed	$0.90 < \eta < 0.95$[3]	1.05	1.11
		3-speed		1.20	1.23
		4-speed		1.32	1.32
	I-AMT	2- to 4-speed	$0.92 < \eta < 0.97$[2]	Same as AMT	Same as AMT
	CVT	n-speed	$0.87 < \eta < 0.93$	1.38	1.38
	IVT	n-speed	$0.87 < \eta < 0.93$[4]	1.88	1.88

*Transmission efficiency (not including differential) for AT, MT, AMT, DCT, I-AMT, and CVT from [24], IVT from [30], and MGT from [41]
[1]Combined efficiency of MGT and motor
[2]Lower value is gearbox efficiency at the vehicle's maximum speed
[3]For two-speed DCT with wet clutch
[4]IVT efficiency dependent on gear ratio, power, and angular velocity [30]

Furthermore, a qualitative comparison of the different gearbox types is presented in TABLE III. *Gearbox Efficiency*, *Gearbox Mass* and *Gearbox Cost* are in relation to the values in TABLE II. The *System Simplicity* is highest for single-speed, MTs, and MGTs, and other gearbox types are considered to be less simple due to their use of synchronizers, clutches, and/or CVT disc plates controlled with electric or hydraulic actuators. *Potential Dynamic Performance* refers to how quickly the vehicle can accelerate and change gears. The DCT is ranked highest because it can change gears without power interruption, and it enables quicker acceleration compared to a single-speed gearbox. For *Potential Drivetrain Efficiency*, it is assumed that the electric machine and inverter can be operated at more efficient points by adding multiple gear ratios. The AMT, I-AMT, and DCT are all ranked the same since they have similar gearbox efficiency, and the CVT and IVT are ranked lower because while they offer a wide range of possible gear ratios, the gearbox efficiency is low. Driving comfort, which is a function of the smoothness of shifting, is not included in this comparison because all gearbox types can reach an acceptable level of comfort with a proper control strategy [28].

TABLE III
QUALITATIVE COMPARISON AMONG DIFFERENT TWO-SPEED AND VARIABLE SPEED GEARBOX TOPOLOGIES

Gearbox type	Potential Drivetrain Efficiency	Potential Dynamic Performance	System Simplicity	Gearbox Efficiency	Gearbox Mass	Gearbox Cost
Single-speed	★★☆☆	★☆☆☆	★★★★	★★★★	★★★★	$
MGT	★★☆☆	★☆☆☆	★★★★	★★☆☆	N/A	N/A

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MT	★★★☆	★★☆☆	★★★★	★★★☆	★★★☆	$
AMT	★★★★	★★☆☆	★★★☆	★★★☆	★★★☆	$$
I-AMT	★★★★	★★★☆	★★★☆	★★★☆	★★★☆	$$
DCT	★★★★	★★★★	★★☆☆	★★★☆	★★★☆	$$$
CVT	★★★☆	★★☆☆	★★☆☆	★★☆☆	★★☆☆	$$$$
IVT	★★★☆	★★☆☆	★☆☆☆	★★☆☆	★☆☆☆	$$$$$

D. *Integrated, Co-Optimized Design of Gearboxes, Electric Machines, Inverters, and Battery Packs*

To achieve the best overall system, a co-optimization process should be used when designing a single- or multi-speed system, including consideration of the electric machine, inverter, and battery. For example, a multi-speed gearbox can enable the downsizing of the electric machine up to 46% for a low-power, urban EV aimed at energy efficiency and cost-effectiveness [44]. Similarly, the study in [45] compares how to best design the electric machine and inverter for single and multi-speed gearbox drivetrains. In [46], different machine designs and their impact on efficiency for different drive cycles for a single-speed gearbox are investigated, showing that system optimization is important even a single-speed gearbox is used.

For systems with multiple electric machines, such as four-wheel-drive vehicles or systems with smaller optimally sized machines combined with a summarizing gear, the system optimization problem becomes even more complex. An approach is proposed in [47] in which the powertrain design and control analysis is split into four layers: topology, component technology, component sizing, and powertrain control. The effects of 44 different combinations of single and multi-speed gearboxes, single and multiple electric machines, and central or distributed power units for a heavy-duty truck were investigated. An integrated powertrain design optimization was performed for each proposed architecture, and a variation of 5.6% in energy consumption and system costs among each powertrain architecture were observed.

In [44], three different powertrain architectures are compared, including: (1) a single-speed gearbox EV, (2) a CVT EV where the CVT simply replaces the single-speed gearbox only, and (3) a CVT EV with co-optimized design and control of the electric machine, inverter, battery, and CVT. The optimal CVT speed ratio, cooling system airflow rate, and sizing of the CVT, electric machine, and battery are determined via co-optimization. The total cost of ownership was estimated to be reduced by 5.9% compared to a non-optimized CVT-based EV and by 2% compared to the EV with the single-speed system.

The study in [48] compares a single-speed gearbox and CVT powertrain with different electric machine sizing for an electric racecar. The CVT setup, despite its lower efficiency and higher weight, achieved a 3.4 s faster lap time than with a single-speed gearbox, further demonstrating the potential of CVTs for EVs. In yet another CVT study [49], the authors perform a co-optimization of the electric machine and CVT design resulting in a 22% reduction in energy consumption.

III. Gear Ratio Selection, Loss, and NVH

A. *Gear Ratio Design and Optimization*

The gear ratio, or ratios, for a multi-speed gearbox, is selected to maximize traction system efficiency while attaining the targeted vehicle top speed and acceleration. For multi-speed gearbox systems, the first gear ratio is selected based on acceleration and gradeability requirements [50], while the top gear ratio is selected to achieve the maximum vehicle speed and good traction system efficiency [24]. When more than two gears are used, the middle gear ratios are selected to further improve efficiency and avoid too large of a step between gears, which may result in longer or more harsh shifting.

When selecting a gear ratio, the tradeoffs between range, low-speed acceleration (launching), gradeability, and high-speed passing can be all be considered, as was done by engineers at GM for the Chevy Bolt EV (Fig. 3). The selected 7.05:1 ratio achieves the greatest range while also having sufficient gradeability, launching, and passing capabilities [51]. Similar tradeoff studies have been performed for two-speed EVs, showing that a DCT can achieve performance targets with proper gear selection while also increasing range by 4% compared to a single gear system [52]. Further improvements for two-gear systems can also be achieved through a combined process of gear ratio and shift schedule design [53]. Additional methods for gear ratio selection also exist, such as the generalized method for manual transmission passenger vehicles proposed in [54], the smooth-shifting methodology in [55] and the genetic optimization algorithms used in [56].

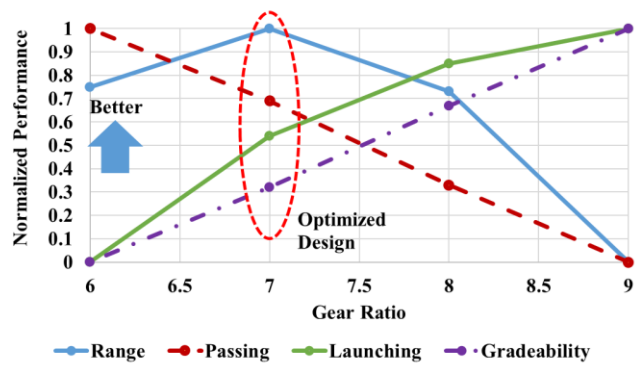

Fig. 3. Normalized performance versus gear ratio for the Chevrolet Bolt EV single-speed propulsion system [51].

B. *Gearbox Losses*

Gearboxes have load-dependent and load-independent sources of loss [57]. Fig. 4 shows gearbox efficiency as a function of input torque and speed at a constant temperature. Much of the losses occur independent of load, even when the vehicle is just coasting, and include speed-dependent bearing, seal, oil churning, gear windage, and gear pocketing losses [51], [52], [53]. The primary loss component, which

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is a function of load, is frictional losses resulting from the meshing of gear teeth. Gearbox losses can be quite substantial, around 4 kW at 7,000 RPM for the 4th gear of a 6-speed MT, as shown in Fig. 5 (a) and (b). A high-efficiency gearbox optimized for EVs, such as the BorgWarner eGearDrive, would have loss closer to 1 kW at 7,000 RPM [61].

Gearbox loss is a function of the gear ratio. Higher gear ratios result in higher loss [62] due to greater speed-dependent losses, especially oil churning and gear windage losses [24], [25], [56]. Higher gear ratios also require more stages of gearing, i.e., two 3:1 gearsets to achieve a 9:1 reduction, with each stage adding to the loss. For this reason, the Chevy Spark EV utilized a high torque, low-speed traction machine, allowing the use of a more efficient single-stage 3.17:1 planetary gearset [6].

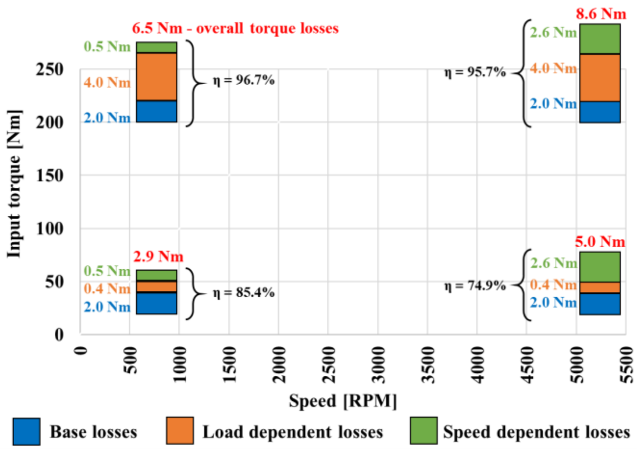

Fig. 4. Example gearbox efficiency and base, load-dependent, and speed-dependent loss in Nm for four operating points [25].

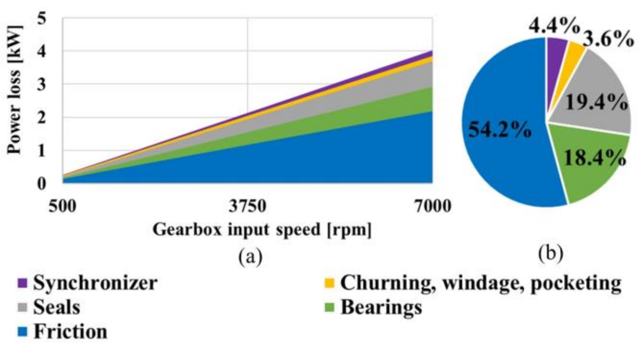

Fig. 5: (a) Loss distribution as a function of input speed for a coaxial 6-speed MT gearbox, in 4th gear, 50% load, 80°C gearbox oil temperature. (b) Distribution of each type of gearbox loss [24].

Importantly, clutches can also add a large amount of loss, potentially accounting for about ¾ of the total loss in DCTs [64]. Minimizing clutch loss is critical to making DCTs an attractive choice for EVs. Traditional belt drive CVTs are also quite lossy, with efficiency around 87% primarily due to the need to provide hydraulic power to maintain pressure on the smooth gearing discs [58], [59], [60].

C. *Gearbox Noise, Vibration, and Harshness (NVH)*

EVs are so quiet compared to ICE-propelled cars, which must comply with maximum noise emission standards [68], that many add external sound generation to comply with government-mandated minimum noise requirements for pedestrian safety. Without the ICE to mask other noises, gearbox, rolling (tire and wheel bearing), and wind noise, as laid out in Fig. 6, dominate the audible noise. Audible noise should be minimized to improve passenger comfort and the perceived quality of the vehicle [69].

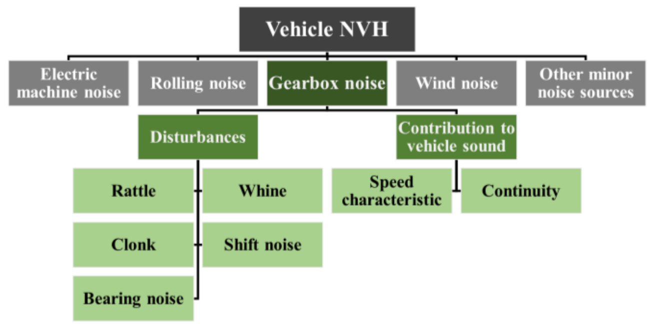

Fig. 6. Gearbox influence on the overall NVH of an electric vehicle [25].

Most existing gearboxes designed for EVs have a single-helical gearset, capable of engaging up to three teeth simultaneously in a smooth fashion and generating minimal noise. A multi-speed gearbox adds many additional sources of noise, though, including clutches, synchronizers, and the gear-changing process. TABLE IV lists gearbox noise types such as whine due to gear meshing, which can be very disturbing due to its discreet sound [70] and scraping and grating noises during shifting due to the synchronizer. These noise sources must be considered at the beginning stages of gearbox development and throughout production and final quality assurance to ensure a good result.

TABLE IV
GEARBOX NOISE AND ITS CAUSES [24]

Gearbox Noise	Cause
Whine	Vibration of gearwheels under load: - Meshing impact - Parametrically excited vibration - Rolling contact noise
Rattling/ Clattering	Vibration of loose parts, caused by torsional vibration of the powertrain: - Idler gears and - Synchronizer rings
Clonk	Knocking noise during beginning loading of components with clearance (gearwheel, joints, shaft-hub connection, etc.)
Shifting Noise	Scraping and grating of the teeth selector when the synchronizer is not functioning properly
Bearing Noise	Running noise of rolling bearings; especially when they are damaged

IV. GEARBOX SHIFT CONTROL, SCHEDULING, AND MAPPING, AND REGENERATIVE BRAKING

A. *Shift Control for AMT, I-AMT, and DCT Gearboxes*

Automatic gearbox shift control algorithms manage the electric machine and gearbox components to achieve a smooth shifting process and minimize the torque interruption at the wheels. Shift controls are a function of several vehicle parameters, such as longitudinal speed, load, acceleration, and braking demand. The algorithms are responsible for controlling electric machine torque and speed while engaging and disengaging the clutches and synchronizers which comprise the gearbox. Because clutches can be engaged while loaded, gearboxes with two clutches like the DCT can be shifted with no torque interruption, while the AMT and I-AMT, which rely on one clutch or only a synchronizer, inevitably have some torque interruption. The shifting process and proposed control algorithms for the AMT, I-AMT, and DCT are described in the following subsections.

AMT Gearboxes – Shift Control with Power Interruption

The AMT gearbox only utilizes a synchronizer, which like all synchronizers, cannot change gears while loaded. Therefore, to change gears, the electric machine torque must first be reduced to zero, as shown in Fig. 7 (time t_1 to t_2). The synchronizer is then disengaged from the first gear at t_2, and the electric machine speed is adjusted to match the speed of the second gear (t_2 to t_3). The synchronizer is then engaged to the second gear at t_3, and electric machine torque is ramped back up (t_3 to t_4) to match the pre-shift wheel torque.

It is possible to use a clutchless AMT in EVs because the electric machine speed and torque can be precisely controlled throughout the shifting process. Research has focused on developing improved controls to reduce shift time of these gearboxes, including [71], which reduced gear changing time to 1 to 1.5 seconds through the use of a two-layered neural network plant estimator and [72], which developed a multi-body dynamic model of the powertrain and a closed-loop motor speed and torque controller.

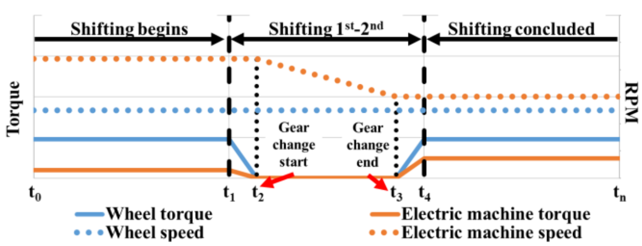

Fig. 7. Simplified diagram of upshifting operation in a generic system, for a constant vehicle speed, with power interruption.

I-AMT Gearboxes – Shift Control with Reduced Power Interruption

The I-AMT gearbox, by using a synchronizer to engage the first gear and a clutch to engage the second gear, can substantially reduce the interruption of torque at the wheels. While upshifting, the clutch is progressively engaged to unload and disengage the synchronizer and allow full engagement of the clutch, all while the electric machine continues to provide power to the wheels, as illustrated in Fig. 8. This process is typically split into two parts, the torque phase (t_1 to t_2), where torque is transferred from the synchronizer to the clutch, and the inertia phase (t_2 to t_5), where the inertia and speed of the electric machine are reduced by fully locking the clutch and engaging the second gear [73].

In the torque phase, electric machine speed is constant, and torque is increased as the clutch is engaged, resulting in zero torque on the synchronizer at time t_2. At t_2, the synchronizer is disengaged, disconnecting gear pair 1, and gear pair 2 is powered via the partially engaged clutch. Clutch loss is very high at this point since the input and output speed of the clutch, the electric machine and gear 2 speeds, respectively, are quite different. In the inertia phase (t_2 to t_5), the electric machine speed is ramped down to match the gear 2 speed by reducing electric machine torque and completely engaging the clutch by time t_5. To compensate for the inertial torque created by the electric machine rotor during deceleration, it is necessary to reduce the machine torque in the t_3 to t_4 range. Downshifting can be achieved by following the inverse of this process.

The I-AMT shift process can be controlled using an optimal clutch speed difference and motor torque reference trajectory as proposed in [74] or by controlling torque with a feedforward controller during the torque phase and a proportional integrative derivative (PID) controller to regulate clutch slip during the inertia phase [36]. In [75], the gear shifting is done with minimal torque interruption by using three control methods: steady-state-like control, reference dynamics-based feedforward control, and tracking error feedback control. Seamless shifting is achieved in [76] by using linear feedforward control during the torque phase and PID control during the inertia phase.

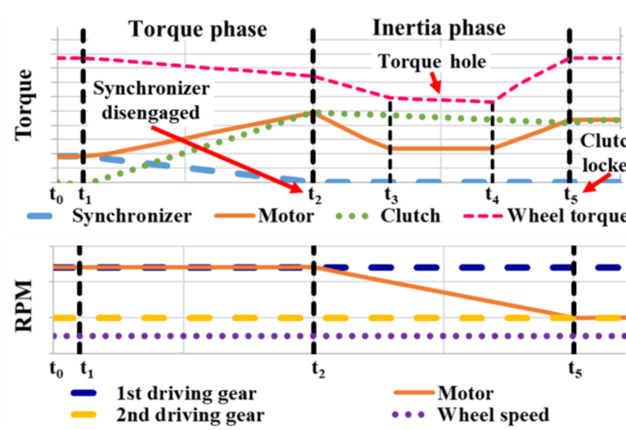

Fig. 8. Simplified diagram of upshifting operation in an I-AMT for a constant vehicle speed, with minimized power interruption [73].

DCT Gearboxes – Shift Control with No Power Interruption

The DCT, as shown in Fig. 2(d), can achieve smooth shifting with no power interruption by simultaneously disengaging the clutch for gear pair 1 and engaging the clutch for gear pair 2. The upshift process is described in Fig. 9, where during the torque phase (t_1 to t_2), the electric machine torque is increased to achieve flat torque at the wheels while clutch 1 is disengaged and clutch 2 is engaged. During the inertia phase (t_1 to t_2), electric machine inertia and speed are

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reduced to match gear pair 2 by completely engaging clutch 2 and reducing electric machine torque to achieve smooth torque at the wheels. The downshift process is simply the inverse of the upshift process.

An optimal shift control algorithm for DCTs is proposed in [77]. An open-loop control algorithm for an electric vehicle DCT was implemented and validated for dynamic drive cycles using an experimental test bench in [77]. To improve performance during gearshifts, a method for accurately estimating the torque transmitted through the clutches was proposed in [78].

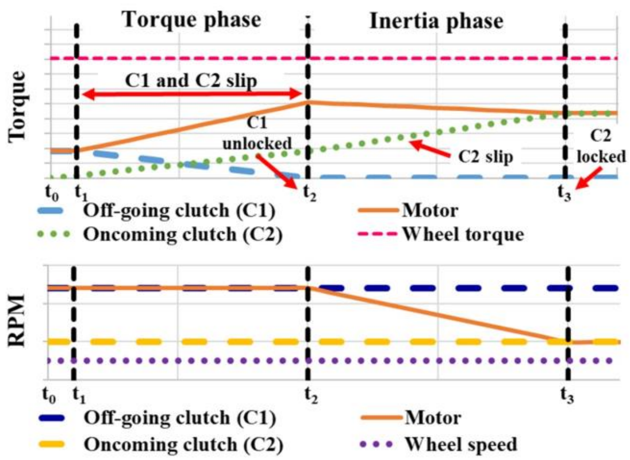

Fig. 9. Simplified diagram of upshifting operation in a DCT for a constant vehicle speed, with no power interruption.

B. *Shift Control Methods for Other Gearbox Types*

Researchers have also focused on developing control strategies for alternative gearbox types, such as the clutchless systems with two electric machines and multiple clutch planetary gearboxes discussed in this subsection.

Clutchless Systems with Two Electric Machines

Clutchless systems, like the AMT, typically have a power interruption during shifting because synchronizers cannot be engaged or disengaged under load. In [79], a second electric machine with a fixed gear ratio is added to a multi-gear AMT-type gearbox. During gear changing, the second electric machine is used to fill the gap in torque, and the study proposes a motor control strategy to achieve this. A similar study was presented by [80], which assessed the energy consumption of a novel four-speed clutchless gearbox driven by two independent electric machines.

Multiple Clutch Planetary Gearboxes

To allow seamless shifting and direct drive, overdrive, and underdrive with a single planetary gear set, dual clutches are used on the input and output of a planetary gearset in [81] and [82]. To allow these three modes, one clutch is connected to the sun gear, and one to the planetary gear carrier on both the inputs and outputs of the gearbox, and the number of gear ratios can be increased by adding additional planetary sets with each ring gear engaged by a separate clutch. A similar planetary gearbox system is investigated in [83], where trial and error and genetic algorithms were used to tune the PID controllers for the gear shifting process, and in [84], where a linear quadratic integral controller is used. Similarly, [85] developed a mathematical model to predict the dynamic nature of the gear topology change to precisely control the gearbox dynamic response while shifting.

A two-speed gearbox utilizing a compound planetary gearset, a gear set with a single ring and carrier and a large sun and a small sun with an additional carrier is used along with three clutches and a control methodology to achieve seamless shifting in [86].

C. *NVH Resulting from Shift Control*

To minimize NVH resulting from shifting, it is necessary to minimize the shift duration and the resulting longitudinal vehicle jerk and vibration [72]. The shift duration, the period from which the gear shift is commanded until torque is fully reestablished at the wheels, should be as short as possible to minimize interruption of power [80], [81]. The jerk should not exceed 10 m/s^3, so it is not perceived by the driver [89], and the RMS of the jerk should not exceed 2.83 m/s^3. Moreover, the jerk should be minimized to reduce the wear of friction components, such as the clutch and synchronizer [90]. Vibration during shifting can be characterized in many ways, including by evaluating the peak to peak or RMS acceleration [69], using a vibration dose value (VDV) [91], or by applying a bandpass filter on longitudinal acceleration [72]. Vibration should be modelled or measured, and the gearbox shift control or mechanical design aspects can be modified to reduce vibration.

D. *Shift Scheduling and Mapping*

A robust strategy, which considers drivetrain efficiency and the dynamic requirements of the vehicle, is necessary to define what gear the vehicle should be in at any given time [85], [86], [87], [88]. The simplest methods control upshifting and downshifting as a function of speed [23], while more complex algorithms consider throttle position [96], acceleration [97], the electric drivetrain efficiency map, braking request, and road grade. Importantly, shift hunting, excessive or unwanted changing of gear ratios, must be avoided by using a delay or hysteretic thresholds. Shift schedules can be categorized into two groups; dynamic shift schedules, which focus purely on achieving the requested speed and acceleration, and energy-efficient shift schedules, which also consider optimizing drivetrain efficiency.

Dynamic Shift Schedule

A dynamic shift schedule selects the active gear to ensure maximum power is always available at the wheels. For a two-speed gearbox, the first gear is selected for low speeds, either first or second gear is selected where the constant output power region for the two gears overlaps, and the second gear is selected beyond the top speed achievable in first gear, as is illustrated in Fig. 10. The point at which the

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gears shift may be selected graphically by defining any point along the constant power region as the upshift and downshift points [23], or an analytical method that considers vehicle acceleration may be used [25].

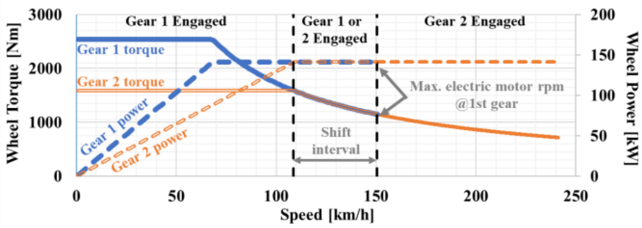

Fig. 10. Example of dynamic shift schedule curve for a two-speed EV gearbox, where shifting is performed to always have maximum power available at the wheels.

Energy-Efficient Shift Schedule

An energy-efficient shift schedule also considers drivetrain losses, much like shift schedules for ICE vehicles which use a higher gear to minimize engine speed and losses when the vehicle is not accelerating. The combined electric machine and traction inverter efficiency map can be used to determine the most efficient gear to operate in, as illustrated in Fig. 11. Using the gear ratios, the efficiency map is translated from being a function of electric machine torque and speed to being a function of wheel torque and vehicle speed. The efficiency maps for both speeds are overlaid, and the shift line marks where it is equally efficient to be in gear 1 or gear 2. To the left of the shift line, it is more efficient to operate in gear 1, and to the right, it is more efficient to operate in gear 2.

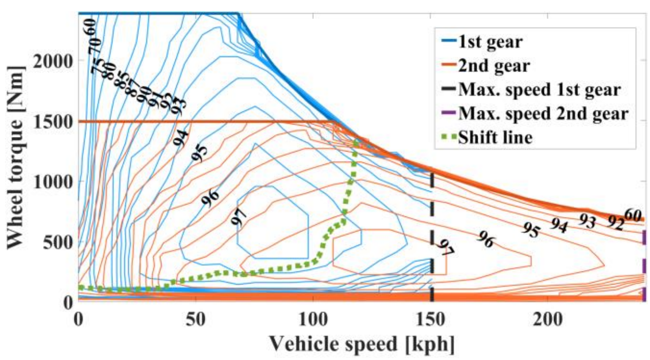

Fig. 11. EV combined traction machine and inverter efficiency when operated in 1st and 2nd gear. To the left of the shift line, operation in the 1st gear is more efficient; to the right of the shift line, operation in the 2nd gear is more efficient.

To prevent shift hunting, a hysteresis strategy can be used to determine when to change gears, as is proposed in [98]. Alternatively, a downshift and upshift line, separated by some velocity from the ideal shift line can be used as reported by [23]. Model predictive control algorithms, by considering road slope and pedal position [99] or vehicle speed and electric machine power capability [100], may be able to achieve better performance in a real application.

E. Consideration of Regenerative Braking in Shift Schedule Design

Unlike ICE vehicles, EVs can recapture the vehicles' kinetic energy while braking, resulting in an extended driving range [101] for both single and multi-speed gearbox drivetrains [102]. The braking is typically performed in a serial method, where the electric motor provides the braking force up to the traction system's maximum limit, and the friction brakes provide additional force beyond that [103]. The amount of energy available to be recaptured can be significant, up to 39% of the total drive cycle energy for the California Unified Cycle (LA92) or 35% for the Urban Driving Dynamometer Schedule (UDDS) [104]. While much of the energy can be captured and store in the battery pack, 10-20% is typically lost due to the electric machine, traction inverter, gearbox, and battery inefficiencies [105].

To maximize regenerative braking energy capture with a multi-speed gearbox, it is important to operate in the gear in which minimizes the loss. Any torque interruption caused by gear shifting during braking may cause the driver to brake harder or react unexpectedly, causing a potential safety issue [106]. To avoid this safety issue, the Porsche Taycan, for example, does not change gears during deceleration [107]. It is desirable to shift gears during braking, though, as was achieved with the cooperative braking algorithm in [108], which only shifts gears during braking under certain circumstances to avoid safety risks. Strategies for shifting during regenerative braking were considered in detail in [104], which pointed out the importance of shifting on long downhill roads where a substantial amount of energy can be recaptured. Shifting during braking was achieved safely in [109] for a four-speed DCT by utilizing the mechanical brake to smooth the shifting process, and it was shown that shifting during braking reduced the energy consumption for the NEDC drive cycle by 4.5%.

V. Energy Efficiency and Performance Benefits Achieved with Multi-Speed Gearboxes

Multi-speed gearboxes have been investigated extensively in the academic literature, and at least a dozen commercial products have been announced. Manufacturers and researchers generally claim that multi-speed gearboxes will reduce drivetrain energy consumption and improve performance. Clutchless AMTs and DCTs are the most promising and common technologies, although CVTs for EVs are under development as well. I-AMTs, IVTs, and MGTs, while they have been investigated in the research literature, have yet to find any industrial applications, likely due to their increased complexity and potentially lower efficiency. The claimed benefits for a variety of commercial and research stage traction systems are summarized in this section.

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A. Results Reported for Commercial Products

Several different OEMs and automakers have developed multi-speed gearboxes, as summarized in TABLE V. Gearboxes with up to six speeds have been developed, and Bosch has even recently announced a CVT product for EVs, which is surprising given the typically low efficiency of CVTs. About half of the gearboxes listed in the table are targeted for passenger vehicles. Of these two are already in production vehicles, the GKN / BMW I8 [110] and the Porsche Taycan [107] gearboxes, both of which are used to improve the acceleration and top speed of performance-oriented electrified vehicles. Formula E race series vehicles have also utilized between 2 and 5-speed gearboxes to improve acceleration, top speed, and efficiency since the inception of the series in 2014 [111]. The other passenger vehicle gearboxes listed are aimed at improving efficiency and claim 5 to 18% efficiency improvements, but none of these claims are independently validated.

Manufacturers, including Mercedes-Benz, Eaton, BorgWarner, Vocis, and Sigma Powertrain, have developed gearboxes for medium and heavy-duty electric vehicles like delivery vans, trucks, and buses. For these very heavy vehicles, multi-speed gearboxes can provide the high torque needed for accelerating on a grade or from a stop and may also provide up to 15% efficiency improvement, as claimed by Vocis [112]. Other manufacturers are also developing multi-speed gearboxes for EVs, including Blue Nexus – a joint venture of AISIN and Denso, Hewland Engineering Ltd., OC Oerlikon Corp. AG, Ricardo Plc, Schaeffler AG, and Xtrac Ltd. [113].

TABLE V
COMMERCIALLY DEVELOPED MULTI-SPEED GEARBOXES FOR EV APPLICATIONS

Company	Gearbox Type	Vehicle Segment	Benefits of Gearbox*	Ref.
Evolute Drive	3-speed	Small-sized / Passenger car	Up to 18% reduction in energy consumption**	[114]
GKN / BMW i8	2-speed	Small-sized / Sports car	Improved acceleration and top speed	[110]
Bosch	CVT	Medium-sized / Sports car / light commercial	Improved dynamic perf. and energy efficiency	[115]
Porsche	2-speed DCT***	Large-sized executive car	Improved acceleration and top speed	[107]
ZF	2-speed	Passenger car	5% increase in driving range	[116]
Drive System Design / MSYS	3-speed	Passenger car	10-15% increase in driving range	[117]
Formula E (FIA)	2- to 5-speed	Competition vehicle	Improved dynamic perf. and energy efficiency	[111]
Eaton	2-, 4-, 6-speed AMT	Commercial vehicles	Improved acceleration, top speed, gradeability, and energy efficiency	[118]
BorgWarner / eGearDrive®	3-speed DCT	Medium-duty commercial fleet truck/ van	Improved dynamic perf. and energy efficiency	[61]
Mercedes-Benz	2-speed	Light to medium-duty commercial fleet truck	Improved dynamic perf. and energy efficiency	[119]
Vocis Driveline Controls	4-speed DCT	Commercial / Minibus	Up to 15% improvement in energy efficiency	[112]
Sigma Powertrain / Mid-Series Transmission	3-speed modular	Commercial / recreational truck	Capability of 1,200 Nm of input torque and 8,000 rpm max	[120]
Sigma Powertrain / Emax Transmission	3-speed modular	Class 8 semi-truck to class 1 truck	Capability of 4,000 Nm of input torque	[121]
IEdrives EVT2 and EVT4	2-, 4-speed AMT	Medium to heavy-duty vehicles	Up to 3,000 Nm input torque or 9,000 rpm max	[122]

*Compared to a single-speed gearbox
**New European Drive Cycle (NEDC)
***Non-conventional DCT

B. Results Reported in Research Studies

A multitude of research studies have investigated the potential of multi-speed gearboxes to improve drivetrain efficiency, as summarized in TABLE VI. This table displays the drivetrain efficiency improvement compared to single-speed drivetrains as a function of the number of gears, vehicle size category, and drive cycle. For these studies, multi-gear drivetrains were modelled, and efficiency improvements between 0 and 23.3% were reported for two to four gear ratio configurations, and the CVT was found to potentially reduce efficiency by 4% or increase it as much as 31.8%, with a large variation in claims between studies.

In general, as more gear ratios are added, there is an efficiency benefit due to the electric machine and inverter being able to operate in more efficient regions, but eventually, mechanical loss due to the additional gears can reduce efficiency. For example, in [16] for a small passenger vehicle and the FTP-75 cycle, a 12% efficiency improvement is predicted for a two-speed gearbox, a 15% improvement for three-speed, and a lesser 11.7% improvement for four-speed. A similar pattern is observed in [123], with a 4% efficiency improvement for a two-speed gearbox, no improvement for a four-speed, and a 2% reduction for a CVT. Conversely, in [17], efficiency only increases with the number of gears, but this is a result of the study ignoring the loss associated with additional gear sets.

The publications in TABLE VI also demonstrate that all vehicle size categories can benefit from multi-speed systems. For instance, [80] shows an improvement of 5.1% to 9.0% for a small-sized passenger car and 0.6% to 5.6% for a full-sized passenger car. Likewise, in [16], an energy efficiency improvement of 11.7% to 31.8% is modelled for small-sized passenger vehicles and 9.0% to 29.8% for full-size passenger vehicles. A small-sized, 872 kg vehicle equipped with a low-power, 28 kW electric machine and a CVT was shown to improve energy efficiency up to 10.9% in [30]. Similarly, [98] combines a low-power, 25 kW electric machine with a three-speed gearbox to increase energy efficiency by 9.3% for a small-sized vehicle. A two-speed AMT gearbox is shown to reduce the powertrain cost and mass for a medium-sized car by 23.1% and 15.6%, respectively, while also increasing efficiency by 2.5 to 4.4% [35]. Heavy-duty vehicles can also significantly benefit from a multi-speed gearbox, as is shown in [124] for a bus with a three-speed AMT gearbox. A 4% improvement in energy efficiency is achieved, and the electric motor power rating is reduced from

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180 kW to 150 kW without compromising the rate of acceleration.

The electric machine and inverter power losses are also a function of the drive cycle, with multi-speed gearboxes tending to be more beneficial for highway operation. This is analogous to ICE-propelled vehicles, which use higher gears during highway driving to decrease the ICE speed and, consequently, increase fuel efficiency. This relation can be observed in [12] for a medium-sized passenger car, in which a two-speed gearbox increases energy efficiency by 2.5% for the urban UDDS cycle and a more significant 4% for the highway HWFET cycle. In [42], the same trend is observed for another medium-sized passenger car, with energy efficiency increasing by 2.8% for UDDS and 16.4% for HWFET via the use of a two-speed gearbox. By applying a CVT [46], a 12.3% improvement in energy efficiency is achieved for HWFET compared to only 3.9% for the NEDC. As discussed earlier, there is a diminishing benefit of additional gears, which is illustrated in [125], where for a four-speed gearbox, a 6% energy efficiency improvement was achieved for UDDS, but no improvement was found for HWFET where speeds are higher, and the drag from the additional gears adds significant loss.

Nevertheless, different energy efficiency improvements can be observed even for different urban driving conditions, as shown in [99]. A 3.2% energy efficiency improvement was found for the UDDS cycle, 3.4% for the NEDC, and even 6.7% improvement for the Japanese J10-15 cycle. In [102], the potential energy savings for a two-speed gearbox were evaluated based on energy recovery from the ReGen for four different urban drive cycles, which has more breaking events, increasing the potential of energy recovery by selecting the most appropriated gear ratio. In order to evaluate different gear shifting strategies, [36] simulated three different urban drive cycles as shifting events are more frequent. The energy efficiency improvement between 7.3% to 11.4% was found.

The efficiency of the electric motor and inverter also greatly impacts the benefit of a multi-speed gearbox. In [42], a relatively inefficient electric machine and inverter are used, with an average efficiency of around 77% for a single-speed gearbox. A two-speed gearbox is found to increase range by as much as 16%. In [16], a relatively inefficient electric machine and inverter are also used, resulting in a very large benefit from applying a CVT. In [126], though, the combined electric machine and inverter efficiency is around 94%, and a two-speed gearbox is predicted to only improve range by 2-3%. Four different electric machines combined with a two-speed DCT are compared, considering a detailed drag torque gearbox model by [50]. A difference of 20% in energy efficiency results was found between the worst and best combined electric motor and gearbox. Since EVs typically utilize electric drivetrains, which are highly optimized for efficiency, it is likely that no more than a few percentage points of range could be gained with a multi-speed gearbox. To conclusively determine the benefits of multi-speed traction systems, it is imperative that more research be done using production electric drivetrains as a benchmark.

VI. Conclusion

Multi-speed gearboxes have considerable potential to improve the efficiency and performance of battery electric vehicles. Most of the traditional gearbox types used for internal combustion engine vehicles have been considered for EVs. AMTs, I-AMTs, DCTs, and CVTs show the most promise. Having multiple gears does allow the electric traction machine and inverter to operate in a more efficient region. A multitude of research studies and manufacturers have touted drivetrain efficiency improvements anywhere from a few percent to fifteen percent or more. The potential benefits are a strong function of drivetrain efficiency, though. A drivetrain that is already 90% or more efficient does not have much room to improve, meaning that a few percentage points of increased efficiency may be more typical. Adding more gears and the associated clutches and synchronizers increase gearbox loss as well, so it is necessary to consider this when evaluating a multi-speed application.

Current production EVs almost solely utilize single-speed gearboxes and are renowned for being nearly silent and providing exceptionally smooth torque. For multi-speed gearboxes to gain acceptance, they must, therefore, maintain the quiet operation and smooth performance drivers have come to expect. DCTs, by utilizing two clutches, and CVTs, which have no inherent gear changing, are most suitable for providing uninterrupted torque to the wheels, but researchers have also proposed methods to smoothen shifting for the simpler AMT and I-AMT. Studies have also proposed some novel gearbox types specifically for EVs, which utilize multiple electric machines or special configurations of planetary gearsets.

While manufacturers have announced more than a dozen multi-speed gearbox products, there are just two electrified vehicles currently being manufactured, which have more than one gear ratio, the BMW i8 and Porsche Taycan. Both utilize a two-speed gearbox and do so with the aim of improving acceleration and top speed rather than efficiency. In the future multi-speed gearboxes may also find a place in higher volume, lower-cost EVs which aim to eke out as much range as possible from the battery pack. This is dependent on whether multi-speed systems can still deliver enough of a range and performance benefit to justify the added cost, weight, and design effort to implement them. Improvements in electric traction machines, inverter efficiency, and power density may also lessen the benefits of multi-gear systems as well. For heavy-duty vehicles, like buses and trucks, which due to their mass, need very high torques to accelerate, multi-speed gearboxes may prove to be more of a necessity so that a lower torque, smaller traction machine can be used.

While the large body of existing research does give insight into how to design, model, and control multi-gear systems, there is a need for more studies, which benchmark multi-gear systems against single-speed production EV drivetrains. Additionally, studies that co-optimize the electric machine, inverter, and gearbox designs would provide a much better comparison than almost all existing studies, which simply use the same traction machine independent of the gearing.

TABLE VI
ENERGY EFFICIENCY BENEFITS OF MULTI-SPEED GEARBOXES OVER SINGLE-SPEED GEARBOXES FOR BATTERY ELECTRIC VEHICLE APPLICATIONS

#Gears	UDDS	NEDC	US06	HWFET	NYDC	FTP-75	J10-15
Small / Passenger Car							
2-Gears	2% [30] 3.2% [99] 2.1% [102]	2.7% [17] 5.5% [80] 3.4% [99] 1% [102] 4% [123]	-	18% [16]	2% [102]	12% [16] 5.1% [80]	7% [30] 6.7% [99] 1% [102]
3-Gears	9.3% [98]	3.8% [17]	-	21% [16]	-	15% [16]	-
4-Gears	2% [123]	4.5% [17] 9% [80] (0%) [123]	-	23.3% [16]	-	11.7% [16] 5.6% [80]	-
n-Gears (CVT)	10.9% [30] (-4%) [123]	5.3% [17] (-2%) [123]	-	30.4% [16]	-	31.8% [16]	13.7% [30]
Medium / Passenger Car							
2-Gears	2.5% [12] 7.3% [36] 2.8% [42] 3% [50]	3.4% [12] 11.4% [36] 3% [50]	2.5% [35]	4% [12] 16.4% [42]	-	4.4% [35]	8.6% [36]
3-Gears	2% [125]	-	-	0.2% [125]	-	-	-
4-Gears	6% [125]	-	-	(0%) [125]	-	-	-
n-Gears (CVT)	5.9% [42]	3.9% [46]	-	13.8% [42] 12.3% [46]	-	-	-
Full size / Passenger Car							
2-Gears	-	1.2% [80]	-	9.4% [16]	-	9.6% [16] 0.6% [80]	-
3-Gears	-	-	-	8.8% [16]	-	9% [16]	-
4-Gears	-	5.6% [80]	-	15.2% [16]	-	14.9% [16] 3.8% [80]	-
n-Gears (CVT)	-	-	-	17.5% [16]	-	29.8% [16]	-
Light-duty truck / Bus							
2-Gears	2.8% [126]	-	-	2.2% [126]	-	-	-
3-Gears	4% [124]	-	-	-	-	-	-

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