American Gear Manufacturers Association

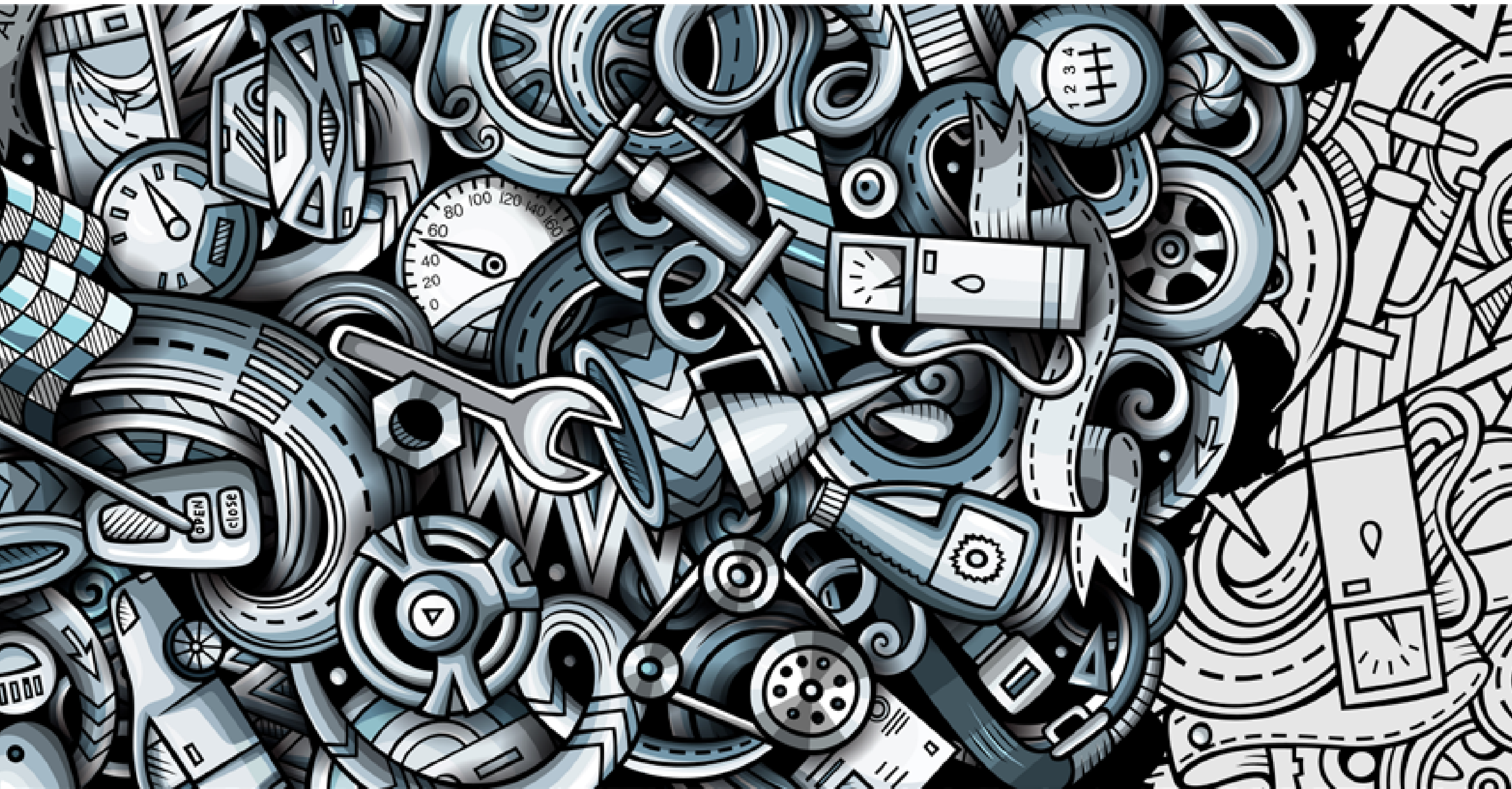
AGMA Electric Drive Technology Committee

WHITE PAPER:

A Gearing-Centric Snapshot of the EV Space

April 2021 AGMA Emerging Technology Committees

contents



introduction

At the 2020 Consumer Electronics Show in Las Vegas, Sony surprised attendees by literally rolling a prototype electric vehicle across the stage. CEO, Kenichiro Yoshida stated, “Mobile has been the megatrend of the last decade. I believe the next megatrend will be mobility.” In December of 2020 during an AGMA CEO Roundtable, John Perrotti, President and CEO at Gleason stated, “Automotive is going through its biggest technology transformation in a century.” These two comments were significant, but so was the year that fell in between. It was a year that no one planned for, and much changed. But as COVID-19 blew up supply chains and brought factories to a halt, investments continued in electric vehicle technology. Sony’s car, the Vision-S, was seen on test runs this past fall. Nikola had a fast rise and fall. And so many others have introduced new technologies in the automotive and truck space.

> **“Automotive is going through its biggest technology transformation in a century.”**
> - John Perrotti, Gleason

Also, during this time, the AGMA Electric Drive Committee met more than a dozen times to discuss the evolving technology. With each meeting the Committee grew in membership and information gathered. The Committee ended the year with almost 40 participants from major OEMs, gear manufacturers, machine tool manufacturers, and suppliers to the industry – all keenly interested in the movement to hybrid and electric vehicles, now called xEV.

This paper was written to fulfill the Emerging Technology Committees’ goal to “identify, investigate and inform AGMA members of emerging technologies that may disrupt or significantly impact the power transmission industry.” It is a snapshot of the current shift in automobile and truck technology, with focus on the gearing.

The paper is divided into three sections. **Part One** provides the big picture starting with the history of electric vehicles to present, and what we should watch for tomorrow. It devotes ample space to research into the evolution of the EV consumer, undoubtedly at the center of this movement. And it wraps up with a list of prominent policy and regulations on emissions and vehicles from around the globe. **Part Two** puts a very gear-centric look on the developments in drivetrain designs. The committee worked to provide information on the diversity in design, high-level technology in the machine tool market, new players with new ideas, different and higher precision manufacturing processes, and the quest for the silent drivetrain. This section also provides some clarity to important questions specific to the gear industry – How will gear manufacturing be impacted by the vehicle technology shifts? And will gear production be outsourced by OEMs? **Part Three** is a trip to the bleeding edge where prototypes are starting the long journey into the possibility of mass production. Explore experimental motor designs, new ideas in battery technology and more. Any of which, if come to true fruition in the years ahead could be labeled a disruptor. But for now, we just have to watch their development.

Happy Reading.

Terminology to note

BEV	Battery Electric Vehicle
PHEV	Plug-in-Hybrid Electric Vehicle
xEV	All forms of Electric Vehicle
ICE	Internal Combustion Engine
TaaS	Transportation-as-a-Service

How Did We Get to Today?

Electric vehicle technology is not new. There are electric car models sitting in museums dating back to the year 1900 and before. The U.S. Department of Energy's (DOE) Timeline: History of the Electric Car credits the invention of the first electric car to a man named Robert Anderson around 1832, while stating that people in Hungary, the Netherlands and the U.S. were tinkering with concepts even before that time. Electric cars were on New York streets in the early 1900s but by 1912, the mass-produced Ford Model T brought the gas-powered car to the forefront. It has been the dominant force over the last 100 years.

It is only in the last 30 years that electric cars have reignited in interest. And only in the last 15 years that they really have gotten their own traction. The U.S. DOE timeline suggests that the introduction of the Toyota Prius, which became the world's first mass-produced hybrid-electric vehicle, and Tesla's move into the automotive market were the two big shifts that have brought electric vehicles (EV) out of dormancy.

This new interest was not born, however, out of a simple calculation of supply and demand, but rather from new regulations and the need for companies and governments to reduce their carbon emissions. There are a number of new policies and initiatives that push to reduce or eliminate fossil-fuel vehicles. This information is detailed later in this section. Timing for mass adoption will hinge not only on carbon-emission regulations, but also factors such as battery cost, life, and disposal, electricity rates, how electricity is produced, charging infrastructure, and road use tax. Each will play a significant role moving forward.

What Should We Watch for Tomorrow?

While regulations may be the driver of the market today, emerging technology will be the driver of the future vehicle space. Even though supply and demand do not support the current trends by themselves, ultimately carmakers have to design profitable products that are desired by consumers. Currently, the main focus is on new battery design as the right innovations could drastically reduce cost of materials, longer ranges between charging, reduced charging times, and increased recyclability. By eliminating the current barriers, manufacturers can reduce the cost of manufacturing the battery electric vehicle while improving consumer-driven adoption of hybrid and battery electric vehicles. Also important are refinements and re-designs to electric motor technology, new innovations like Transportation-as-a-Service (TaaS), and ultimately autonomy. Auto manufacturers can look forward to many changes in the coming years while gear manufacturers will see some real changes and opportunities in this space.

The Evolution of EV and the Consumers

The Evolution of the EV and the Consumers

EVForward™ is the largest EV study of the next generation of EV buyers. It is an agile solution that provides unprecedented insight into the attitudes, behaviors, and opinions of a new generation of EV buyers.

Mike Dovorany, Vice President, Automotive and Mobility for the market research firm Escalent, researches the consumers of electric vehicles and has presented his results at many industry events. He has stated that, "Early adopters of electric vehicles and hybrid-electric vehicles in the 2000s afforded a higher income, education, and were younger than the typical new car buyer. The households that purchased an xEV had three or more cars and were more willing to contort their lives around electric vehicle limitations." Buying and driving an xEV car, in most cases, supported a "green" philosophy that was rooted in combating climate change. There was also economic interest in hybrid vehicles allowing for less trips to the gas pumps and savings over the lifetime of the hybrid vehicle. BEV, PHEV and hybrid cars that were produced were light, small, and economical as they were more expensive to produce than their internal drive engine equivalents. As a result, many government incentive programs for electric vehicle purchases were enacted. These incentives removed a barrier to market for consumers interested in these products.

Then vehicle products evolved changing the landscape for the consumers.

From the early adopters in the 2000s to the new adopters in the late 2010s, xEV buyers changed. This new generation of buyers were less extreme, more mainstream, states Dovorany. "Buyers came from a wider variety of households including households with children, more apartment dwellers, and single-car households." Dovorany is the main researcher for Escalent's 2020 EVFORWARD™ − the largest, most comprehensive study of the next generation of EV buyers. The study utilized advanced analytics of more than six million variables over 10,000 new vehicle buyers. The study results identified true EV intenders regardless of EV education through proprietary algorithms. The results showed findings that challenge pervading thinking. One result is that Dovorany has come up with six unique EV buyer personas. But the overarching results showed that 85% say xEVs are the future and many people have a more positive view on them than they did only a year ago. Yet electric vehicle purchase intention remains low. Last year, only 1.4% of U.S. vehicle buyers leased or purchased an EV.

A Deeper Dive into Cars and their Sales Data

The electric vehicle segment more than doubled from 2017 to 2018. According to TrueCar data, "Gen X is buying the most EVs at 39.8%, followed closely by Millennials at 34.9%, but Boomers are actually the ones buying the greatest mix of all green vehicles." Consumers of EV and hybrid vehicles have evolved with the technology. Probably the best way to highlight this is to take the two vehicle lines that are said to have changed the industry, Toyota and Tesla.

The leader in hybrid-electric cars in the 2000s was Toyota with its Prius line of cars. The Toyota Prius family of vehicles sold 5,562 vehicles in the U.S. in 2000 and by 2012 reached its height in U.S. sales at 236,655, according to Car Sales Base. Early consumers purchased the car for its environmental impact, but as it gained popularity, many Prius owners purchased the car on simple economics. They utilized the incentive programs and appreciated the savings at the pump that the hybrid cars afforded over the lifetime of the vehicle.

Contrast that with the influence of Tesla. Founded in 2008, Tesla first sold vehicles in the U.S. in 2014, at a modest 16,689 units. Almost immediately, Tesla began to build a cult following, and was able to increase sales in just six years to reach 235,000 vehicles sold in the U.S. in 2020 (499,550 globally), according to Car Sales Base. There are many other manufacturers that sold electric and hybrid vehicles during this time, but the contrast of Toyota's "green-forward" focus with the Prius; and Tesla's performance-forward focus, provides the perfect example of the drastic shift in EV consumers between 2012 and 2020.

It cannot be said better than by Sam Fiorani, Vice President, Global Vehicle of Auto Forecast Solutions in a recent video post: "The idea that Tesla buyers are snapping up Model 3s and Model Ys just to get away from their ICEs is absurd. Tesla builds a great performance car. To get that kind of performance from a $60,000 Model 3 would have taken a $150,000 exotic car just a few years ago."

The rise of Tesla changed the landscape for all electric and hybrid consumers, but it also changed the landscape for manufacturers. While the top automobile manufacturers were already investing in R&D in this space, Tesla's relatively rapid success enticed other manufacturers and would-be players from outside the industry to also invest in this space.

Some economists in this space have speculated that 2020 will be looked back on history as the 'tipping point' for xEV finding solid footing in the vehicle market.

Electric Vehicle Sales in 2020

The market has burst wide open with record investments, new players, new partnerships, and new products in 2020. Sony arrived on the scene debuting their own electric car in January at CES 2020. Collaboration announcements by Daimler and BMW; Ford and Volkswagen; Toyota, Mazda and Subaru; and more brought a wave of press releases. Fiat Chrysler and PSA group became Stellantis. Then major car companies announced collaborations with technology companies, technology companies made announcements of their own vehicles, and a long list of newcomers threw hats into the ring. Names like Lucid Motors, Fisker, Nio Limited, and XPeng Motors, entered the vehicle space creating excitement and all eyes on the next few years as all of this technology works its way in front of consumers. And finally, the announcements of companies' commitments to going all electric spilled out of press rooms around the globe. General Motors announced in January 2021 that it plans to be carbon neutral by 2040 and aspires to eliminate tailpipe emissions from new light-duty vehicles by 2035. Time will hold the key as to whether or not these ideals will be reached. But it will be a wild ride in the meantime.

Some economists in this space have speculated that 2020 will be looked back on history as the 'tipping point' for xEVs finding solid footing in the vehicle market. Even with a global pandemic interfering with pretty much everything, over 450 models (300 BEVs and 150 PHEVs) were available for sale in 2020 (EV-volumes.com). Among these models were electrified SUVs and pickups, and electrified versions of iconic vehicles came on the scene. Ford debuted electrified versions of the Ford F-150 and Mustang, and GM put an electric motor in their Hummer. Some research firms believe that the xEV market in the U.S. will reach 6.9 million units by 2025.

Global sales for xEVs topped 3.2 million for 2020. This compares to 2.26 million for the previous year. Despite the pandemic, nearly 1.4 million electric vehicles were registered in Europe during 2020. In a year that saw a 20% reduction overall in vehicle sales, BEV and PHEV sales in Europe saw a 137% increase over 2019 numbers. It was the first time that European consumption of EVs was higher than China's.

Policies and Regulations Driving a Reduction on Carbon Emissions

Across the globe, there has been a recognition of the need for the reduction of carbon emissions. As the globe reaches a total of 100 million vehicles, governments and institutions have published a number of policies and regulations in this space. More than a dozen countries have announced some kind of ban on new internal combustion vehicles. There are also areas within some countries, like California and Quebec, that have enacted their own regulations. A list of some of the most significant can be found below. And in recent days, the Fuels Institute (reported by NACS) released a report that explores the impact on the fuels industry of outlawing sales of new conventional vehicles. This new paper presents them in three main categories: environmental impact, market readiness, and consumer and stakeholder impact.

UNITED STATES

NATIONAL

- **Corporate Average Fuel Economy (CAFE Standards)** - https://www.nhtsa.gov/laws-regulations/corporate-average-fuel-economy
  NHTSA's CAFE standards regulate how far our vehicles must travel on a gallon of fuel. NHTSA sets CAFE standards for passenger cars and for light trucks (collectively, light-duty vehicles), and separately sets fuel consumption standards for medium- and heavy-duty trucks and engines. NHTSA also regulates the fuel-economy window stickers on new vehicles. In March 2020, NHTSA and EPA set the model for fuel economy and carbon dioxide standards that get more stringent, increasing 1.5% each year from model years 2021 through 2026. These standards apply to both passenger cars and light-duty trucks.

OF NOTE: **CALIFORNIA**

- In December 2020, California instituted a ban on the sale of new gasoline-powered vehicles by 2035.
- **Hybrid and Zero-emission Truck and Bus Voucher Incentive Program (HVIP)**
  Provides incentives to purchase the cleanest medium- and heavy-duty trucks.
- **Clean Cars 4 All**
  Incentivizes lower-income California drivers to scrap their older, high-polluting cars and replace them with zero-emission, PHEV, or HEV.

CANADA Canada is also reviewing the possibility of a Canada-wide electrification minimum.

BRITISH COLUMBIA

- **Zero-Emissions Vehicle Act (ZEVA)**
  In May 2019, British Columbia passed the Zero-Emission Vehicles Act. The ZEV Act requires automakers to meet an escalating annual percentage of new light-duty ZEV sales and leases, reaching 10% of light-duty vehicle sales by 2025, 30% by 2030, and 100% by 2040.

QUEBEC

- In December 2020, Quebec's Minister of Environment, Benoit Charette, announced that the province would ban ICE vehicles in the province as of 2035. This policy was part of a broader $6.7 Billion Green Economy Initiative.

MEXICO As part of a pact with mayors of Paris, Madrid, and Athens, in 2016 the mayor of Mexico City agreed to impose a ban on all diesel-powered cars and trucks in their respective cities by 2025.

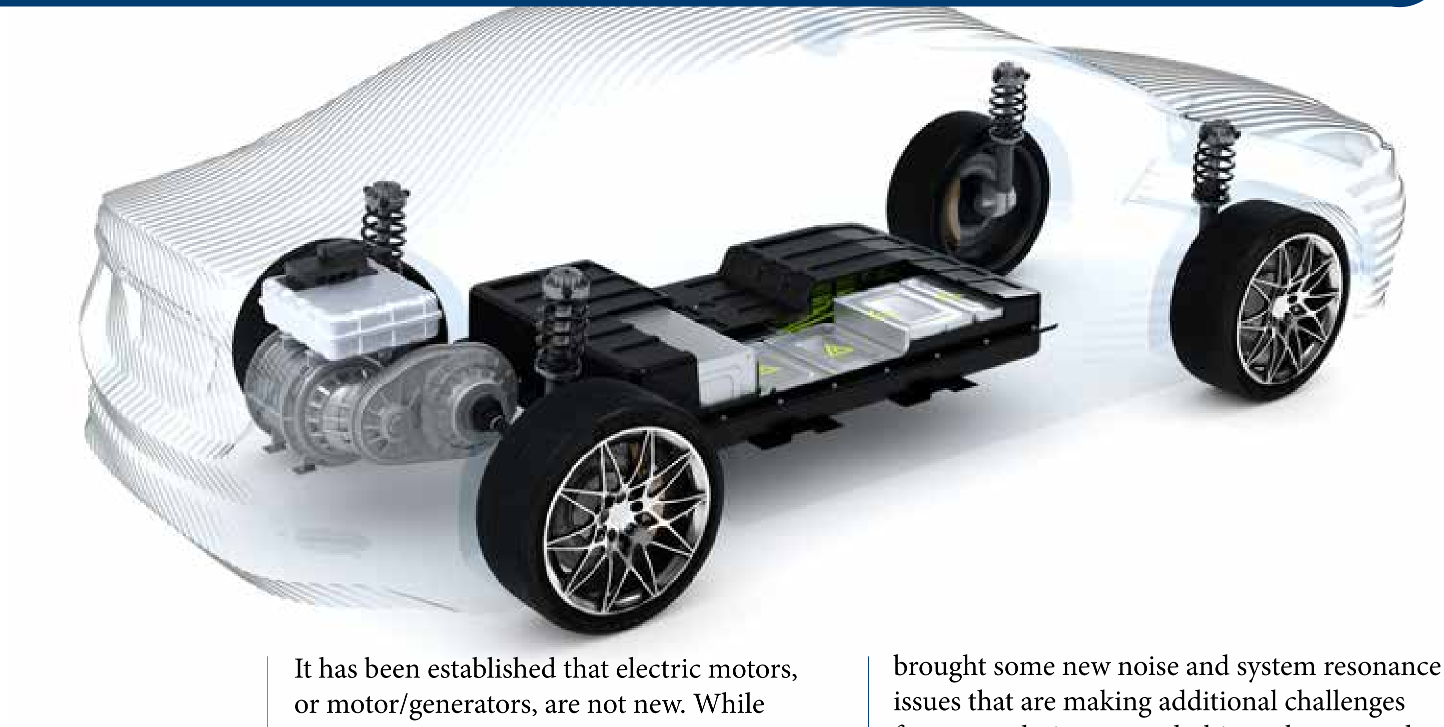
BRAZIL It should be stated that Brazil has a ban on diesel cars dating back to the 1970s.

NORWAY Norway is the leading country when it comes to converting to electric cars. In December 2020, 87% of all new car registrations were chargable cars, with 66.7% being fully electric. Norway is hoping to reach the goal of banning the sale of all new gasoline and diesel cars by 2025.

UNITED KINGDOM The United Kingdom recently moved their date on eliminating the sale of fully fossil-fueled vehicles from 2040 to 2030 and 2035 for hybrid vehicles.

EUROPEAN UNION The European Commission, led by Denmark and the Netherlands, is being lobbied to set a date to ban sales of new gasoline and diesel cars across the European Union to align the transportation sectior with climate goals. In July 2017, France aimed to end the sale of gasoline and diesel vehicles by 2040. In 2019, it was reported that the country has a mobility law that will also facilitate the rollout of electric vehicle charging stations. Denmark began pressing the European Union in October 2019 to ban the sale of cars powered by gasoline or diesel fuel by 2030. Germany put a ban on new fully fossil-fueled cars by 2030.

CHINA China has a unique plan for new vehicle sales starting in October 2020 (Nikkei Asia) that all new vehicles sold in 2035 be "eco-friendly." The rule gives way for Japanese manufacturers, who specialize in hybrid engines.



One critical point to establish is that there are fewer gears in an electrified drivetrain than in a traditional ICE drivetrain.

It has been established that electric motors, or motor/generators, are not new. While regulations have been setting the stage for a push to electrification, technology has helped. Not to be underestimated is computing power. The availability of cheap and powerful computing has led to the needed advances in design software and machine tool technology so that today manufacturers are able to experiment and push the limits on more complex and advanced vehicle design.

While some gear manufacturers are working with partners at OEMs that they have worked with on components for internal combustion engines for years. They are also seeing new faces in this space whose understanding of gears are different and they provide a new perspective on the components. On paper, the challenge for gear manufacturers should be on the new designs in motors. Unfortunately, not only is there a new standard for design, but there is a new standard for noise. Noise, vibration, and harshness – referred to often by just NVH - presents some of the biggest challenges currently in the design of precision components like gears and bearings. Even though the trend towards reduced drivetrain noise is not new, the removal of the internal combustion engine includes the removal of much of the noise from traditional automobiles. Electric drives are much quieter. However, the new drivetrain designs have brought some new noise and system resonance issues that are making additional challenges for motor designers, and ultimately gear and bearing manufacturers.

The noise issues have pushed design teams to work in a holistic fashion on the electric drivetrains. Every component from the gears to baffle to housing is constructed with the complete unit in mind. All aspects of design including machine tools, heat treat, and finishing processes are being reviewed and tweaked. Drivetrains are now being design as unified systems. This is a challenge for teams with competing expertise.

How Many Gears are Needed for Electric vs. ICE?

One critical point to establish is that there are fewer gears in an electrified drivetrain than in a traditional ICE drivetrain. In general, the electric motor provides more torque across a wider speed range than an ICE and thus, requires less gearing. Taking hybrids out of this discussion because they are essentially both an electric and internal combustion drivetrain, a typical internal combustion automobile or light truck has, on average, 24 gears. Within the transmission there are three to four planetary gear sets (3-6 planet gears in each set) for an average total of 18 gears. Adding the six gears of a common final drive and differential (parallel or hypoid pinion, parallel or hypoid ring, and the four differentiating pinions) arrives at a standard number of gears that is approximately 24 for an average automobile. Averaging the various configurations for an electrified drivetrain, the committee consensus is that the standard is four multiplying gears and then four differentiating pinions, for a total of eight gears. There are some e-Axles that have six gears in the differential for a total of 10. The basic count is that there is about one-third as many gears in an electrified drivetrain than in the traditional internal combustion automobile.

Electric Motors Run at Higher Speeds

In addition to the production of more torque, regenerative braking requires performance on both flanks of the gear.

Electric motors and internal combustion engines are different technology, so the gears too are different. Conventional combustion engine transmissions have optimal efficiency between 1,000 and 2,500 RPM and will shift (in automatic transmissions) up to seven times on average to reach 55 MPH. An electric motor's peak torque is higher than combustion engines and is delivered over a wider speed range. With less gearing, EV drivetrains will attain higher motor RPMs as the vehicle speed increases. In addition, the smallest, lightest, and lowest cost motor designs will operate at higher speeds. There are fewer stages needed in the electric motors, between two and four, and the first and second stage have much higher speeds. There is discussion of some high precision motors reaching 30,000 RPM in coming years. Increases in RPM bring a lot of new issues to reach efficiency. Heat transfer, speed, lubrication and cooling, and thermal efficiency will be more critical as the speeds increase. Surface speeds are a real challenge for the gear industry as there will come a point when even the thickest lubricants will evaporate from the surface of a heated high-spinning gear tooth.

A New Problem for Gears, Regenerative Braking

In addition to the production of more torque, regenerative braking, found in xEV requires performance on both flanks of the gear. This has resulted in the need for higher precision and durability on the gears. Some gears require hard finishing after heat treatment. One committee member pointed out, "In many cases, OEMs have designed compound planetary gearsets which provide the robust solution to this requirement, but it comes with a cost. Compound gears need a new method of manufacturing and manufacturers have been using power-honing production machines to perform the finishing of these gears." Additional input discussed the use of low-pressure carburizing heat treating to provide more uniform case depth along the surface of gear teeth that have been honed or ground.

Will Electric Drivetrain Be Core for Manufacturers in Transportation?

One of the biggest questions the committee worked to find an answer to was: With fewer gears in transportation, will gear manufacturing no longer make sense to keep in-house by the OEMs? Or is there an opportunity for a bigger segment of gear manufacturers to supply the auto industry?

The answer is as complex as the current vehicle market, but generally speaking the committee

Consensus from the AGMA Electric Drive Technology Committee is that those that make gears in volume today will do it tomorrow.

consensus was that those that do it today at volume will do it tomorrow. Big OEMs already have the infrastructure and staffing to keep gears in-house. Michael Berhan from Ford stated, "If and when the additional volume doesn't justify new lines and tooling, OEMs may acquire them from a gear supplier." But in general, he sees gears staying in-house for large OEMs. "We have the expertise and people. Plus, nobody wants to ship around a bunch of gears if you don't have to. That is one component where you want to minimize any issues that moving may cause." One question for some OEMs is should they start investing in batteries? Or continue to focus only on making gears and gearboxes? There are many non-mechanical products in these cars, too. Companies have to figure out where they will find the value-add. But it is a different story for new players in the industry as several committee members noted that they are most likely having their gears made outside their vehicle assembly facilities.

"It is really hard to justify the capital investment for making gears," states Jack Masseth, recently retired from Meritor, "and there are a lot of businesses out there that are really good at making gears. So newer companies will be reaching out to them to make the gears. And it is not a who will tool up a line for gears." Added Michael Berhan, "It is also a question of heat treatment, which by itself is a challenge. Heat treat for gears is a big investment. Companies that are new in this space will have to be able to both 'cut and bake.'" On the truck side it is agreed that truck manufacturers are most likely going to contain their gear capability in-house. One thing that may change this is transmissions. An e-Drive transmission may only have 4, 5, or 6 speeds in difference to the current technology that has 10-speed and as high as 15-speed. There may be manufacturers who start to just produce the e-Drive transmissions to maximize capacity.

Another important note to be factored in for gear manufacturers is that it is not only the electrification that is different, but also the commercialization. Companies are utilizing different technical specialists in the design process and it is changing how companies are

Dedicated Hybrid Transmission
Schaeffler

At the current time there are four distinct xEV designs that the committee has noted:

- Direct drive in each wheel
- Central drive 2-wheel
- Central drive 4-wheel
- 4 gear hubs

looking at how to create components – even critical ones like gears and bearings. Their suitability in future high-speed electrified drivetrains need to be assessed not only based on speed but also size and overall inertia, utilizing physics. Hence, further assessment criteria can be m/s for gears and speed x pitch diameter (n.dm) for bearings, rather than just speed (RPM). Additional design and weight optimization of the gears and bearings may be necessary using advanced materials technology and surface treatments to improve their overall performance and efficiency at higher speeds.

Configurations in xEV – Cars and Light Trucks

There are not too many design changes needed for gears in electrified drivetrains for automobiles and light-duty trucks – consumer pickups, vans, and delivery vehicles. There are incremental changes as you move from light trucks to heavy trucks, class 4 and beyond, which will be discussed shortly. But at the most basic level, the gear design for electric cars and consumer pickups is similar. From OEMs to supplier to basic technology, there are similar issues. It is the economics and fleet size that is different. This has led to new vehicle designs. Lightweight vehicles are becoming popular – especially for vehicles smaller than a standard UPS truck – putting a drive on each of the rear wheels, using all parallel axis, creates a vehicle that is one speed and used for a more specific in-city drive. But these designs are still being tested and changed. Committee members do not see the drive in each wheel in the short-term future.

At the current time there are four distinct xEV designs that the committee has noted:

- Direct drive in each wheel
- Central drive 2-wheel (vehicle driven by 1 e-Axle)
- Central drive 4-wheel (some vehicles have 2 e-axles per vehicle)
- 4 gear hubs (some consist of a gear and a pinion) – e-wheel drive

NVH Concerns – Cars and Light Trucks

There are no standards in automotive for noise. Essentially the standard is 'noise free.' Or as one committee person stated, "as close to zero as you can humanly get for the cost." Generally, it is considered that profile is most of what changes for noise. Surface finishing is a contributor, but the profile and accuracy is where most of the noise energy is held and thereby the thing that will be addressed most. Committee member Tony Werschky from Delta Research stated that, "NVH and efficiency is pushing the capabilities of production gear manufacturers, and machine tool manufacturers to deliver. With these requirements, the planetary gearset and Ravigneaux Gearset has presented itself as a power-dense, efficient solution to a demanding EV transmission."

Configurations in xEV – Trucks Class 4-8

At the most basic level, trucks are designed to be driven miles with as few failures as possible. The magic number is one million miles. Trucks require a different design than a family automobile. In the truck space, electrification is not new. Off-road vehicles for mining and agriculture have been using electric motor technology for years. Some in-city vehicles like dump trucks and buses have been electrified. Moving this technology to fleets is a question of having the infrastructure in place to support the shift. The long-term economics favor electric. The vehicles require less in fuel and maintenance costs, despite having a larger initial price tag. Applying the technology to road fleet environments is more complex, and at a most basic level it comes down to the cost of ownership over the life of the vehicle. John Bennett, CTO of Meritor, spoke on this topic at the 2019 AGMA Motion + Power Technology Expo (MPT Expo). In a side-by-side comparison at the time of his presentation, diesel trucks were more cost effective than matching electric vehicles in a direct comparison. He then went on to discuss some of the factors that will affect this comparison. First, BEV have a lower operating cost. There are significant savings in fuel costs, and maintenance cost can be as much as $2,000 to $11,000 less annually, depending on miles, duty cycle, emissions, and engine type. He stated that the gap would tighten further as the projected decline in battery cost increased demand. Beyond a one-to-one comparison, government incentives would be the most significant game changer in this space. California HVIP incentives have changed average seven to eight-year payoffs to immediate. These incentives are creating the space for the development of electric vehicles in the Class 4-Class 8 vehicle space.

NVH and Backlash Concerns – Trucks Class 4-8

Configurations of electric motors for trucks is a little more conventional than automobiles.

In current design, axle and transmission noise is more easily heard with e-Drives due to the elimination of engine noise. The challenges are even higher with high capacity large gearing. Ground spiral bevel and hypoid gears are now being produced to help with the noise. They are also being ground because of the need for very tight backlash control. Backlash control is driven by the need for continuous regeneration at higher torques than are historically seen. This is called coast side loading. It was generally not looked at seriously in the past, but is now extremely critical and is certainly a result of the EV movement. Grinding offers much higher consistency. Several committee members stated that they do 100% grinding in transmission work. The bulk of the axle gears are 90-degree hypoid/spiral bevel which are ground as well. One member stated, that if anything, "noise requirements and backlash control will need to get tighter." This will probably lead to finer pitch gears that are ground and possibly lapped or ultimately it will lead to a different design entirely. Lapping helps with the frictional and higher harmonic noise. While it does modify profiles, it is not a lot. And testing has shown, lapping on top of grinding results in the quietest, most consistent gearing. Right now, lapping without grinding is not completely reliable and without grinding backlash cannot be adequately controlled. "Out of our total research dollars going into hypoid gearing right now, a big chunk of it is going into maximizing coast performance," stated Craig Anderson from Meritor. The e-Drive truck market wants to capitalize on regeneration and those torques can be equal to the drive torques. In vehicles that move people, there is a limit for how much deceleration is comfortable for the person. But in the case of delivery trucks, that is getting pushed continually.

He noted that there is a balance. If one pushes the fine pitch, there have been issues in bending strength. There is a fine dance in what can be done to diminish noise while not creating difficult obstacles in other ways. While there is no question in the truck industry that fine pitch helps with noise, it is difficult to overcome strength issues. Configurations of electric motors in trucks varies. One is to put the motor and transmission mounted directly to the axle. These are called e-Axles. In some cases, companies are using conventional tandem axles and are replacing diesel engines with electric motors. An e-Axle (motor and transmission mounted on the axle) does take up slightly more space than a conventional axle, but it provides a complete drivetrain and opens up a re-think on how a truck can be configured. For the forseeable future, e-drives will contain some sort of transmission. Whether it is a 2, 3, or 4-speed will change, but a transmission will stay.

Truck motor speeds are 4,500 – 6,500 RPM with the possibility of these numbers getting higher in the future, but not at the 30,000 RPM expected in automobiles.

Applications and regulations will be major drivers in electric propulsion in trucks. EVs will be more readily seen in in-city delivery and places where emission reduction is crucial, distances are short, and high-speed charging is accessible. Long-haul vehicles have the challenge of carrying the weight of batteries combined with the need for consistent charging infrastructure. And, of course, the use of these vehicles in warmer, more stable temperature zones will increase before they drive through Northern winters. Fuel cells may be considered a more suitable option for long-haul vehicles by industry experts.

The automobile industry has spent the last century investing and perfecting the development of the internal combustion engine (ICE). Changing from this technology will be profound and felt across the globe. Several countries have already cited end dates for the final production of internal combustion engine automobiles. Production engineers are already executing plans on retooling plants as they contend with a period of production of both standard ICE and electric vehicles. And not only the major OEMs, but also many new players are pouring research and development dollars into how to rethink the technology for optimal success. This global change will have a profound effect on gear manufacturers and suppliers to the gear industry. It will not be an overnight change but incremental stages as the industry brings in the new technology. Currently, there is not a standard way to build an electrified vehicle. This paper will show some of the designs that have more mainstream support as designers continue to experiment and push limits.

Machine Tool Sector

One of the key questions for the gear industry is: Does the machine tool technology exist to manufacture the gears needed for electric drivetrains? The short answer is ***Yes!*** The technology exists to support the needs of the industry. There is a very powerful technology to utilize for some of the more complex problems brought by electric motors.

There is a long-standing tradition of machine tool manufacturers working diligently to adapt to the changing needs of their clients. Members of AGMA's Electric Drive Committee both from machine tool manufacturers and also precision gear manufacturers attested to the fact that the industry has the machine tool capability to meet the needs currently. There are no gaping holes in the machine tool market for auto or truck. There are refinements and tweaks that will happen, but in general the technology is ahead of where it is needed.

Drilling down a little into the machine tool market, maturing computer technology and machine kinematics played a substantial role in manufacturers' ability to produce high precision components just in the last decade. Kinematics at its most basic definition is "the branch of mechanics concerned with the motion of objects without reference to the forces which cause the motion." When applied in the machine tool market, it becomes how the parts of the machine tool are relating to each other as a machine is set to do a task. Huge advances in computing power in the last 20 years gave machine tool manufacturers the ability to utilize huge calculation power within the machines.

Once the computer technology was in place, the next step in this precision design story is software development. Increases in computer power at lower costs allowed for more general manufacturing use of high-tech solutions like digital twining and simulation software. Most machine tool providers are moving toward a completely closed-loop system for gear manufacturers.

While there are no techniques being used exclusively for manufacturing gears for EV applications, one interesting trend is the return of a couple of older techniques that have been brought back with high-tech precision. These techniques are honing and skiving. While more than 100 years old, the precision work that these techniques now can be used to achieve is only possible through the development of computer technology and machine kinematics. It is an example of the machine tool industry working to fulfill the demands of the gear industry.

Here are a couple of examples of components produced using new skiving machines:

Compound Planetary Gear

Planetary Ring Gear

Photos from Delta Gear Research

Committee member, Tony Werschky of Delta Research, discussed using skiving now for the production of ring, compound planetary and layshaft gears. Skiving he said is "a method of gear cutting where the part and tool are spinning synchronously in different axes. This allows the skiving tool to cut the leading edge of the part without clipping the trailing edge of the formed gear. It is only in recent years that machine kinematics has reached the maturity to allow tool manufacturers the ability to make these flexible and highly productive machines." Here are a couple of examples of components he has produced using new skiving machines:

Gear Power Honing is the latest technology in gear hard finishing. BEV motor transmissions typically produce more torque, higher impact pressures and require performance on both flanks of the gear due to regenerative braking. This has resulted in the requirement for higher precision and durability on the gears (including the ring gears). This translates into the need for hard finishing of the gears after heat treatment. And in many cases, OEMs have designed compound planetary gearsets which provide the robust solution to this requirement; but, it comes with a cost. With compound gears having two separate gears close together that are traditionally timed to each other, the old method of manufacturing whereby gears are hobbed and ground using a threaded grinding wheel is no longer viable. To solve this problem, gear machine tool manufacturers are finishing these gears using power-honing production machines. These machines perform in different ways than their traditional gear hobbing & grinding counterparts but with the same accuracy and stock removal.

A Note on Inspection

Requirements for inspection have changed in the development of the electrified drivetrain. Waviness analysis, which was not as critical in the past, today requires greater precision on elements of the flank form. The use of lasers for high density scans of full flanks is more commonly used today. All of this is driven by the new requirements of the xEV sector.

One item of note is the dramatic increase in the amount of analysis that is now taking place underneath the start of the active profile in the root area as gears are designed with longer teeth to increase contact. This is done in an effort to potentially reduce noise.

"The key is going to be how the OEMs and gear designers and manufacturers harness that information and take advantage of it — or put it into play for the application. This will lead to improvements in the applications because I think it is still in its infancy here with the capabilities of looking at the entire tooth – root and fillet. I think there is a lot more to come in what can be gained from all that data," stated Michael D'Arduini from Gleason.

Heat Treat Sector

Not to be overlooked is heat treating. Whether it is a pinion or sun gear moving power through to the wheels, these gears will need to be heat treated. Heat treating will allow the gear to obtain the proper surface hardness and case depth.

Technology of heat treating has not fundamentally changed in many years. Probably the biggest shift in the last 20 years was the introduction of low-pressure carburizing, or as it is also called, vacuum carburizing. This process allows for a more uniform case depth along the flank of the gear. It allows the case to be uniform for precision grinding or honing.

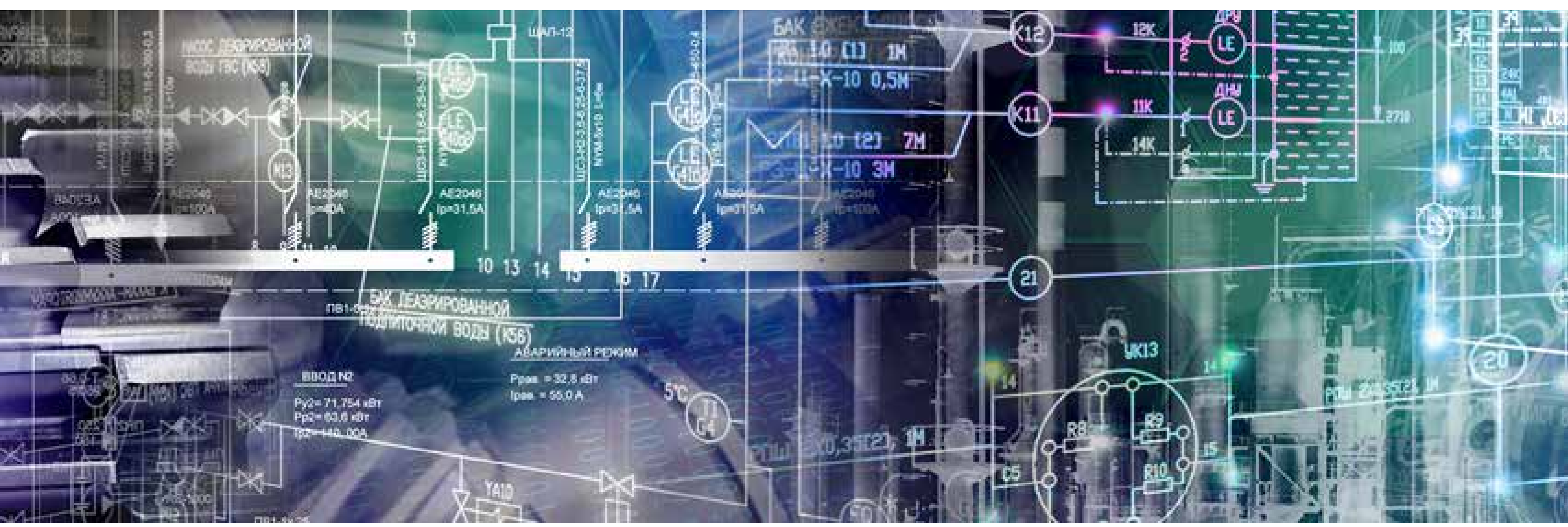
Power honing and grinding can create issues if the heat treating method does not provide a uniform surface hardness and case depth throughout the tooth after these processes. A low pressure carburizing process is being used in EV programs to help provide these gears better tolerances after finishing and retain their specifications.

Today, new methods in heat treating are being developed using simulation software to develop the correct quench rate and part placement during the process. This simulation development helps to better understand the temperature cooling rate to understand the potential distortion.

Fuel Cells

Not to be overlooked when discussing electric vehicles, there is also a lot of development in the hydrogen fuel cell space. A fuel cell uses hydrogen to produce electricity that can be the power source for vehicles. Fuel cells can be more compact and recharge faster than batteries. There are several ways that the hydrogen is being produced for these fuel cells, but for the most part, they are less energy-efficient than batteries – today. If this changes, there will be changes in the marketplace as this is touted by some to be a better fuel source in the long term.

As previously mentioned, the reason for this paper started out of the emerging technology efforts of AGMA's committees. There was a need to inform the industry of where the electric vehicle market was today but also to look at technologies that could be deemed 'emerging' in the growing electric vehicle space. The following examples run the gamut from research, to proof of concepts, to small production. At this time all of these technologies are still in the 'proving' stage, but they do have the potential to be disruptors in this space in the future.



BATTERY TECHNOLOGY DEVELOPMENTS

Money is being poured into developing more efficient battery technology. Currently, the players that are able to better solve at least one of the biggest three issues: cost of production, use of rare-earth minerals, or recyclability, will gain market share in this arena. Beyond pure battery development there is a lot of activity in the areas of Vehicle to Grid (V2G), and Wireless EV Charging. For the purpose of this paper, two technologies outside the general discussion of battery technology are worth discussing, as they may have profound impact on this space if the technology carries out to mass production.

Metal Amorphous Nanocomposite Materials (MANCs)

Dr. Michael McHenry (and group), Carnegie Mellon University in collaboration with the National Energy Technology Laboratory (NETL), NASA Glenn Research Center, and North Carolina State University.

Michael McHenry is a professor of Materials Science and Engineering at Carnegie Mellon University. He and his team are synthesizing metal amorphous nanocomposite materials (MANCs). These glassy magnets are able to maintain lower temperatures than silicon steels when spun at high speeds, making them an alternative for motor development. Research is pointing to the possibility of creating much smaller motors to deliver comparable power. Additionally, his group has a patented material that enables the use of lower cost permanent magnets which do not require rare earth materials. He received funding by the DoD to scale up his work at the NETL and NASA Glenn Research Center. Possible applications include vehicle motors, aerospace applications, and power generation. More information is available in an article about the technology from 2018 here: https://phys.org/news/2018-11-magnetic-materials-motors-future.html

There is a video on this technology here: https://www.nasa.gov/feature/glenn/2020/fantasy-to-reality-nasa-pushes-electric-flight-envelope

And as recently as November 19, 2020, NASA Glenn Research Center discussed soft magnets as an integral part of their research into Electrified Aircraft Propulsion (EAP). https://www.nasa.gov/feature/glenn/2020/fantasy-to-reality-nasa-pushes-electric-flight-envelope

Al-air: New battery design touts 1,500 mile range

Trevor Jackson, an engineer and former officer in the UK's Royal Navy, through home experimentation, may have found a new safe electrolyte that can be used for an EV battery. His technology is touted to provide an EV with a 1,500 mile range. The batteries are constructed from plastic, aluminum, and a non-toxic, safe electrolyte. They can be air-freighted wet or dry and are not flammable.
https://www.automotivelogistics.media/electric-vehicles/al-air-a-better-battery-for-evs/40079.article

Research in Fuel Cell Development: High-power direct borohydride fuel cells (DBFC)

Researchers at the McKelvey School of Engineering at Washington University in St. Louis have developed high-power direct borohydride fuel cells (DBFC) that operate at double the voltage of conventional hydrogen fuel cells. Their research was published June 2020 in the journal *Cell Reports Physical Science.*

ELECTRIC MOTORS THAT PRODUCE MORE TORQUE

There are many new designs that have come out into the public light over the past few years that, if the technology is brought successfully from experiment to production, could change the cost, environmental impact and performance of electric motors.

EVO Axial Flux motor – developed by Avid Technology

The AVID Group, a spin-off of ComeSys, was established in 2008, putting electric vehicle powertrain research and development as a stand-alone company. In 2010 they developed parts for the Ecotricity Nemesis supercar, which broke the UK EV land speed record that year. In 2017, the company reached an agreement with GKN to acquire the IP, design, manufacturing, and sales of the EVO Axial Flux electric motor technology, and they announced a project with Caterpillar in 2018 to develop a new battery storage system for electric machinery, which led the company to expanding to North America in 2019.

EVO is touted as 'one of the highest usable torque and power densities on the market.' Its patented lightweight composite rotor gives the motor low inertia. It has an achievable power density of >10kW/Kg. This in turn delivers higher efficiency over a transient operating cycle and improved drive response compared to conventional motors. Its application possibilities include traction motors for electric and hybrid buses and trucks; traction motors for high-performance electric supercars; P1/P2 configuration hybrids; direct drive of propellers for aero and marine; and high-performance generators.
https://avidtp.com/product/evo-motors/

Hunstable Electric Turbine (HET) – developed by Linear Labs

Linear Labs brings together a father/son duo. Dad spent a career designing the electrical infrastructure for nuclear power plants. His son founded a streaming service that he sold to IBM in 2016 for $150 million and is investing some of the money into this new motor design.

The HET is "an exterior permanent magnet circumferential flux 4 root machine. Innovative concepts are introduced in the magnet structure and operation at the core of the HET, resulting in large amount of torque generation." This motor is said to produce twice the torque in half the size of other leading motors. And it can be used in automotive, aerospace, and robotic applications.
https://linearlabsinc.com

MAGSPLIT and Pseudo Direct Drive (PDD) – developed by Magnomatics

The company Magnomatics, established in 2006, has developed two products based on magnetic gears. The Pseudo Direct Drive (PDD), and MAGSPLIT. The technology came from the University of Sheffield, where the company continues to have strong links.

Magnomatics developed Pseudo Direct Drive (PDD), a direct drive high torque, low speed e-machine that 'achieved a step-change in continuous torque density compared to that of equivalently cooled PM machines while maintaining very high efficiency.' It integrates a non-contact passive magnetic gear within a permanent magnet brushless machine. This design allows the motor to be used in place of a conventional motor/gearbox combination where the solution needs high continuous torque at relatively low speeds. This application is best suited for aerospace, actuation, marine propulsion drives, oil & gas applications, some wind turbines, and rail traction systems. Their MAGSPLIT utilizes magnetic gearing principles that allow a highly integrated power split unit which does away with epicyclic gears. This drive system has two rotating elements and can be powered by conventional inverters. It is a solution for a dedicated hybrid transmission.

SupraMotor – developed by Festo

Festo built a compact, superconductive claw pole motor with a solid-state cooling. Called SupraMotor, the drive is characterized by a very compact design, a high holding torque and a long-life electric direct cooling system. The motor is optimal for low speeds with very high torques. "If a load has to be held, the drive uses no energy even at maximum holding torque."
https://www.festo.com/group/en/cms/13088.htm

conclusion

The xEV market is in a state of flux. While electric motors ran vehicles on New York city streets in 1900, they have come a long way and can now be seen zooming down streets in Silicon Valley. This paper assists AGMA to "Identify, investigate and inform AGMA members of Emerging Technologies that may disrupt or significantly impact the power transmission industry."
Four years ago, when AGMA started a more concentrated effort in watching emerging technologies, electric drive was not in the initial mix. It took another eight months to bubble up to a point where it was expanded enough for members to get together and be able to speak critically on the topic, and the Board supported adding it as a focus area. A lot has happened in the years since. This paper represents high-level discussions for a common good within an industry. The individuals that contributed to this paper were not financially compensated, and AGMA did not take any funds for the paper's production.

Whether or not xEVs take off, one thing is sure — gears are important components and manufacturers across the globe will continue to refine designs, fight tighter tolerances, and develop new techniques. And hopefully, they will continue to bring these findings to the neutral ground of the AGMA Electric Drive Technology Committee to continue the discussions.
We encourage you to reach out to us to learn more about the committee. Or visit www.agma.org where you will find articles, videos and more information on emerging technology.
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CREDITS

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