Addressing Critical Challenges from Smog-Causing Pollutants to Climate Change:

The worldwide effort to address climate change has brought about regulatory policies that are transforming the automobile and trucking industries. In attempt to reconcile their customer's need for mobility with global mandates to dramatically curtail carbon emissions, car and truck makers are investing in carbon reducing innovation as never before. Electric hybrids, and battery and fuel-cell electric vehicles are emerging to diversify motor vehicle powertrains. In 2018, demand for electric vehicles remains low relative to today's internal combustion engines (ICEs). Nonetheless, car manufacturers, aware that transition to zero emission powertrains will require a major shift in technology, infrastructure and consumer preferences that will take decades to accomplish, are developing solutions aggressively today so as to position themselves for the future.

What do these changes mean to CET's business which is focused on pollution control for internal combustion engines? While today the consensus points to an eventual transition to battery powered electric vehicles, or BEVs, how and when that occurs remains largely uncertain. What *is* certain is shifting technologies in the transportation industry will create opportunity and growth for CET for decades to come. Further tightening of tailpipe emissions and increasing numbers of hybrid electric powertrains that demand specialized aftertreatment solutions will pose new challenges for OEMs. Corning Environmental Technologies will continue to serve the transportation industry as an innovation partner, applying its deep materials science and systems engineering expertise to develop solutions that enable greater performance and fuel efficiency while answering the call for stricter emissions control.

CET's business spawned from a world-wide movement to clean up the air. In the 1960s and early 1970s, millions of cars had been emitting hundreds of millions of tons of noxious pollutants into the atmosphere. Smog shrouded cities like London, New York, Los Angeles, and Hamburg, posing severe public health effects that kept residents with respiratory or heart conditions indoors. The Clean Air Act of the early 1970s established the Environmental Protection Agency (EPA) and called for regulations on motor-vehicle exhaust. The EPA mandated a 75% reduction in noxious emissions from all new cars by 1975.

Catalytic converters, which combine oxygen with carbon monoxide and unburned hydrocarbons to produce carbon dioxide and water, had previously been applied to smoke stacks and forklifts but never with the durability and at the scale required to equip millions of automobiles. Materials scientists and systems engineers at Corning developed a ceramic composition, cordierite, with the low thermal mass and strength to serve as the core of the catalytic converter in motor vehicles; at the same time, they developed the extrusion method that enabled the ceramic substrate to be manufactured efficiently in volume. By 1975, Corning Environmental Technologies had placed approximately 3 million ceramic substrates in new automobiles.

Even as catalytic converters successfully addressed a worldwide crisis of air pollution, the technology's future in automobiles was uncertain. Aftertreatment was not regarded as a long-term solution because engineers were convinced the pollution problem could be solved through a more elegant re-design of the internal combustion engine. As government regulations grew more stringent, however, CET continued to develop more effective and durable ceramic substrates and filter products for gasoline and diesel applications.

Forty-five years later, CET has accumulated more than 600 patents and delivered more than 1.5 billion pieces (substrates and filters). With the help of catalytic converters smog levels in LA have dropped by 85 percent. In total, more than 4 billion tons of hydrocarbons and nitrogen oxides have been kept from the air and 40 billion tons of carbon monoxide was contained.

The next great challenge: sustaining mobility while confronting greenhouse gases (GHG) and Climate Change

Just as concern for smog-causing pollution in 1970s spurred regulation that drove the development of ceramic substrates for catalytic converters in automobiles so the need to address climate change today drives the development of technology in vehicles that reduce and/or eliminate carbon emissions.

In 2016, transportation accounted for the largest portion, 28%, of total U.S. greenhouse gas (GHG) emissions, according to the EPAs Inventory of Greenhouse Gases and Sinks. Of that amount light duty vehicles produce the majority, about 60% of the total. The transportation industry -- including cars, trucks, buses and airplanes – accounts for approximately 15% of global greenhouse gases. The United Nations 2018 report calls for a 45% reduction of greenhouse pollution by 2030.

In addition to emitting zero emissions, all electric vehicles are more energy efficient than ICE vehicles, which lose a large part of the energy they derive from fossil fuels to heat. While Internal combustion engines run 20% to 30% conversion efficiencies, EVs, by contrast, use 90% to 95% of the input energy to power the movement of the vehicle. Aggressive carbon reduction targets that are driving the adoption of electric vehicles are being set worldwide.

- Europe has set a target for reducing grams of CO2 per kilometer by 25% by 2020, 40% by 2025 and 60% by 2030;
- California 36% by 2025;
- China 30% by 2020 and 50% by 2025.

China and California have initiated mandates to promote EV adoption. China's New Energy Vehicle (NEV) mandates for PHEVs, BEVs, and Fuel Cell EVs (FCEV) requires car companies to sell 10% NEVs in 2019 and 12% in 2020 or lose their license to sell all vehicles. Depending on the mix of powertrains, however, from 2% to 5% of NEVs could potentially meet the ten percent target in 2019. California has a target of 22% ZEVs (same as NEV) in 2015. Similarly, that target could potentially be met with 8% sales, depending on powertrain mix.

How automobile manufacturers are responding

In an effort to comply with government regulations to reduce or eliminate carbon emissions, automobile manufacturers have developed an entire spectrum of powertrains with different levels of electrification:

- **Stop and Start and Mild Hybrids** On one end of the spectrum are the powertrains that rely mostly on ICEs. Stop/Start solutions use electricity to turn the engine off when the vehicle is at rest and on again when it starts to move. Mild hybrids use small electric motors to increase fuel efficiency by turning off the engine when coasting or braking and in some cases by employing regenerative breaking.
- **Traditional Hybrids and Plugin Hybrids** Full hybrids, either conventional or plugin (PHEV), use a combination of electric and ICEs to achieve greater fuel efficiency. Traditional hybrids operate on battery at low speeds and switch to ICEs at higher speeds. PHEVs typically run on battery for 30 to 60 miles and, when battery charge runs out, transition to an internal combustion generator that charges the battery even as it powers the vehicle. PHEV owners today can charge their vehicles at home with a slow charger in a standard 120 outlet electric that takes approximately 13 hours or a faster charger on a 220 outlet that takes 4 to 5 hours.
- **Battery Electric Vehicles (BEV)** A zero-emission vehicle, BEVs operate on an electric battery and can range from 80 to 330 miles before re-charging. The majority of BEV owners have home chargers that enable them to charge overnight and/or hook up to chargers at work.
- **Fuel-Cell Electric Vehicles (FCEV)**Also a zero-emission vehicle, emerging fuel cell vehicles convert stored hydrogen and oxygen from the air to electricity that drives the onboard electric motor. Most fuel-cell vehicle owners live in California where fuel-cell refueling stations are located.

Factors Influencing the Rate of EV Adoption

While few deny the automobile industry will undergo a sea change in coming decades, viewpoints vary concerning how it will change and how quickly. When the price of BEV reaches parity with ICE vehicles, most agree sales of BEVs will reach a tipping point and adoption will be able to accelerate without subsidies. Several other factors, such as government mandates, BEV range, charging infrastructure, and the cost of fuel also factor into the equation. A wide range of factors will influence EV adoption.

Government Push: mandates and policies

Government policy represents one of the most critical drivers of EV adoption. While EVs remain substantially more expensive than ICE vehicles, incentives are necessary to attract early adopters. Currently in the US, EV and some PHEV purchasers have received tax credits of up to $7500 if new vehicles meet certain specifications such as kilowatt hour capacity.

The effect of government policy on EV adoption can perhaps best be illustrated in the Nordic region. The stock of electric cars in Denmark, Finland, Iceland, Norway and Sweden has grown steadily since 2010, reaching almost 250,000 cars by the end of 2017 and accounting for roughly 8% of the global total of electric vehicles (EVs) in 2016. The Nordic region has one of the highest ratios of electric cars per capita in the world.

In Norway, which has a 39% share of electric car sales, taxes can run as high as 150% of the import cost of the vehicle. All taxes are omitted for electric vehicles. In addition to price incentives, Nordic countries have enacted local policies such as reducing or waiving parking fees and tolls for electric cars.

Where pro-EV policies have been taken away, sales of EVs have been hurt. After 2015, Denmark reported fewer sales of EVs than its Nordic neighbors due to policy shifts less favorable to EV adoption in 2016. Scaling back tax incentives resulted in a 60% decrease in EV sales.

Customer Pull: Total Cost of Ownership

Industry observers agree that until the price of electric vehicles fall, promotion of EVs is unlikely to succeed. Most analysts expect price parity between ICEs and EVs to occur sometime between 2025 and 2029. Currently, EVs are mostly being marketed to smaller car segments, the buyers for which tend to be price sensitive. The 2018 Nordic EV Outlook reported that the vast majority of electric car owners would not buy EVs without economic incentives that achieve cost parity.

Once EVs reach cost parity they do enjoy advantages such as lower maintenance (oil changes, for instance, are unnecessary) and fuel savings. The cost of electricity in most countries is far below the cost of gasoline or diesel. In China, drivers have high annual mileage and a higher gas-to-electricity ratio which makes the total cost of ownership of an EV lower. That, coupled with government incentives and regulations, explains why China has the highest number of BEV sales of any major market.

Supply and Infrastructure: Battery Technology and Raw materials

Every designed and commercialized EV today depends on some type of lithium-ion based battery, which offer relatively high energy density, specific energy and long life cycle. Lithium-ion battery technology has matured over the last 25 years for use in portable electronics (cell phones and computers). Currently, electronics take 25% of the market, and EVs represent 57% of the market but the percentage is increasing rapidly.

EVs require rare-earth metals for motor magnets and lithium for batteries. Depending on projections for the number of EVs by 2030, which by some estimates could reach as high as 125 million to 160 Million (International Energy Agency), to meet the need lithium production would have to double or triple what production is today for all applications. Although Corning research indicates that battery supply will be enough to cover demand over time, difficulty obtaining the necessary raw materials could delay production. The world’s second largest deposit of lithium, for instance, lies in Bolivia, 12,000 feet above sea level with the nearest port 500 kilometers away.

Power Grid and Charging Infrastructure

Early adopters of electric vehicles charge their vehicles at home or at work. The Nordic EV Outlook 2018 study, for instance, reported that 94% of all power outlets used for EV charging in Nordic countries are in homes or work places and that 92% of EVs are used for commuting. Electric car owners tend to have more than one car and rely on ICE vehicles for at least a portion of use because EVs do not have enough charging reliability for longer trips. Public charging infrastructure is viewed by many as crucial for further EV adoption. Fast charging stations are required to reach those without access to charging at home or work. According to KPMG Global Automotive Executive survey, the difficulty of setting up a user-friendly charging station has led 62% of executives to believe that BEVs will fail and fuel-cell vehicles, which could potentially use existing fuel infrastructure to transport hydrogen, will eventually become the ZEV of choice.

The deployment of charging stations will require business models that make charging station operations and maintenance viable without subsidies. How to best charge, aggregate and control EV load on the grid also is a fundamental issue that will have to be resolved. Chargers can add significant load to household power demand, particularly during peak hours and cold days. Depending on the electricity infrastructure, a spike in demand could stress the distribution grid.

Could charging stations become like todays petrol or gas stations? Reservations on the successful deployment of this approach are relative to cost of installations, necessary grid upgrades, and storage capacity required. Experts believe improvements in battery technology will eventually enable charging in minutes instead of hours, but as a report from the International Renewable Energy Agency (IRENA) points out, to facilitate high voltage fast chargers in large numbers will likely require advanced solutions, such as in-situ electricity storage, to avoid disruption to the grid.

The rate of EV adoption, and the degree to which EVs will curtail carbon emissions, also depend on the nature of the power grid. Countries with inexpensive and clean energy have an advantage in promoting EV adoption. In the Nordic, where per capita EV adoption is the highest, four countries are pooled in a single power market, Nord Pool, which strengthens reliability of electricity supply and offers prices frequently the lowest in Europe. The low-carbon intensity of the electricity system which largely consists of renewables – hydro, nuclear, wind – means EVs have a much greater environmental impact. The use of 4 million electric cars would produce 40 times less emissions from the same type of ICE cars, according to the 2018 Nordic EV Outlook. The IRENA report states that “electricity must be deeply decarbonized for average efficiency BEVs to have a significant advantage on CO2 emissions.” Battery-electric vehicles provide zero-vehicle-emissions driving (for both carbon dioxide and pollutant emissions), but the “upstream” CO2 can be substantial, for example in countries with dominant coal power generation. Electric grids must be considerably de-carbonized (to 600 grams (g)/ kWh or less) for EVs to have a CO2 advantage relative to similar sized hybrid internal combustion engine (ICE) vehicles. For instance, in Denmark, where the renewable energy share is about 80%, the gC02/passenger is on the range of 30g CO2/km. In Kazakhstan or Poland, where coal dominates energy generation, the figure is close to 100g per km, which is close to the level of an efficient petroleum vehicle.

Estimates for EV Adoption

Estimates for EV adoption derive from the varying aspirations of states and organizations and underscore the uncertainty surrounding EV uptake. LMC automotive forecast predicts that "Internal combustion engines will still power 85% of new US cars in 2025. Based on its industry research, Corning estimates that BEV adoption will grow from 1% of worldwide automobile sales in 2017 to 5% in 2025 to approximately 15% in 2030.

A handful of International agencies have issued reports that attempt to predict EV adoption for 2030. According to the 2018 EV Outlook, "supportive policies and cost reductions are likely to lead to significant growth in the market uptake of EVs." Taking existing and announced policies of major countries and the EU into account, the EV Outlook estimates the number of electric light-duty vehicles on the road will grow from 3 million in 2017 to 125 million by 2030. "Should the policy ambitions continue to rise to meet climate goals and other sustainability targets," the report said, "then the number of electric light duty vehicles on the road could be as high as 220 million in 2030 – 130 million battery electric and 90 million plug-in hybrids, respectively."

The EU30@30 campaign aspires to achieve 30% market share for electric vehicles in the total of all passenger cars, light commercial vehicles, buses and trucks by 2030. Norway's ambition is to have 4 million EVs by 2030, a 15-fold increase from 2017, slightly more than 1/3 of which would be PHEVs.

In 2016 California's governor issued an executive order to call for 1.5 million ZEVs on the road by 2025. In January 2018, a new executive order called for a target of 5 million ZEVs in by 2030.

Various and sundry reports in the media have highlighted aggressive electrification plans from automakers. In December of 2018, Bloomberg reported that automakers worldwide plan to introduce 127 battery-electric vehicles in the next five years. Volkswagen AG reported it plans to begin development of its last ICE gasoline and diesel models in 2025 for eventual sale in the early 2030s. VW also reported plans to launch fully or partly electric versions of its line-up of more than 300 cars, vans and trucks and motor cycles by 2030. General Motors announced plans to roll out 20 models by 2023; Toyota Motor Corp committed to more than 10 electric models early in the next decade.

Opinions also differ regarding the future mix of powertrains. According to a 2018 KMPG Auto Executive Survey, the majority of auto executives from leading brands worldwide believe fuel cell electric technology, while currently behind lithium-ion battery in its application, stands a better chance of becoming the zero-emission solution for the future. While media reports tend to predict dominance of BEVs after 2030, by 2040 most auto executives surveyed believe the future will bring a mix of drivetrain technology. By 2040, they say, the market will be split evenly among BEV, FCEV, ICE, and hybrid powertrains, each representing about 25% of the market.

What *is* Certain: Electrification Presents Challenges and Opportunities for Innovation

As meeting regulatory mandates with traditional ICE powertrains becomes too expensive, tightening CO2 regulations will drive the industry toward electrification. Hybrid vehicles represent the next phase in the path to electrification because they curtail CO2 pollution by improving gas mileage while offering greater affordability and range than BEVs. A 2017 IHS Powertrain Forecast anticipates hybrid production will increase by 25% within the next decade, compensating for the decline in traditional ICE powertrains. Indeed, in the Nordic region, where electrification is progressing most rapidly, the market share for PHEVs is outpacing that of BEVs. In Norway, according to the 2018 Nordic EV Outlook, "BEVs stabilized at about 20% of the total market, and most of the incremental growth of electric cars achieved in the past two years in terms of market share is due to PHEVs."

Since CET arose in the 1970s, tightening government regulations have led to challenges that in turn create opportunities for its innovation-driven business model. In electric hybrids, these challenges stem both from changes in engine design and from the vehicle's requirement, when accelerating to higher speeds, to abruptly switch from its electric to its combustion engine. This design poses "cold start" problems because catalysts cannot perform at low temperatures and will release pollutants such as carbon monoxide, hydrocarbons and nitrogen oxides. Without addressing the cold start problem, hybrids will continue to emit more pollution then ICE vehicles do.

Emerging powertrains that offer greater gas mileage are designed with smaller engines that operate at lower temperatures to save energy from fuel. These advanced engines also present cold start problems and, at the same time, emit more particulate matter. Tighter limits on particle emissions as indicated in Real Driving Emissions protocols in new European Union (EU) and China regulations will require new aftertreatment innovations.

Corning's Role on the Road to Electrification

Further regulation on ICEs and the push toward electrification are driving CET's innovation roadmap. CET will continue its clean air mission with aftertreatment solutions for advanced ICE powertrains. At the same time, it will play a key role in the longer-term evolution from combustion to electrification with research and development efforts focused on enabling catalysis at lower engine temperatures. Product development teams will continue to innovate solutions to lower thermal mass in ceramic substrates and explore micro structures and additives that decrease weight and make ceramic material more porous. Through electrically conductive materials and heating devices, researchers also will search for ways to sustain the light-off temperatures of catalysts when engines run cold. Anticipating ever more stringent regulations in leading automotive markets like China, CET will pursue the next generation of particulate filters.

In today's advanced powertrains, filters and substrates will need to be integrated in solutions with minimal footprint. CET's R&D team includes scientists and engineers versed in materials, modelling and simulation, electrical engineering and chemical engineering. These teams will be challenged not only with developing new products but with engineering processes that lower the cost of manufacturing through fewer steps and better materials.

Continuing Its Clean Air Mission

Just as it did in the 1970s, environmental crisis is providing new challenges and opportunities for growth at CET. Whatever form the powertrains of the future take, CET innovation will play a key role in the technological changes that enable the automotive industry's transformation to cleaner transportation. Between the introduction of Low Emission Vehicle II (LEVII) tailpipe standards in 1997 and the start of LEVIII standards in 2015, the automotive industry has faced a total tightening of emissions standards of about 97%, according to "Review of Vehicular Emissions Trends," a technical paper by Corning scientists. New cars today are 98% cleaner than in 1970 in terms of smog-forming pollutants. The 2015 LEVIII and US tier 3 implementations will further employ the energies of Corning engineers and scientists through 2025. And as hybrids lead the path toward electrification, CET will deliver advanced after treatment solutions that enable OEMs to meet tightening regulations. In addition to solving emissions related challenges, Corning scientists will apply their talents to other components of the automobiles of the future such as light weight windshields, interior touch screen displays and the connectivity necessary for autonomous vehicles.