Freight movement is an important enabler of economic activity. We saw substantial growth in freight movement in the industrialized countries over the last three decades, and growth is accelerating in emerging markets with the rise in demand for consumer and industrial goods. Global road transportation of freight is also a large consumer of energy as well as an emitter of air pollutants and greenhouse gases.

Trucks accounted for about 16 million barrels per day, or 17 percent of global oil demand in 2017, and are projected to be responsible for nearly one-third of global oil demand growth by 2040. Diesel fuel consumption in road transport has grown a staggering eightfold since 1970.

Road freight vehicle greenhouse gas emissions are currently three gigatonnes of CO$_2$-equivalent and are projected to more than double by 2050. The bulk of greenhouse gas emissions and growth are for heavy-duty vehicles, which travel substantially more miles than smaller trucks and use more fuel per mile. Road freight vehicles are also important contributors to NO$_x$, fine particulates, and SO$_2$ emissions. Air pollution is the single greatest environmental health risk, accounting for one in eight deaths globally.

Despite these energy use and environmental challenges, road freight transport has not received the same policy attention as passenger cars. For example, only four countries have historically had fuel efficiency standards for medium- or heavy-duty trucks, while 80 percent of light-duty vehicle sales are covered by fuel efficiency standards. This workshop explored
the potential of electrification in reducing oil consumption and emissions of greenhouse gases and air pollutants in trucks. Given the larger size and greater distances traveled by medium- and heavy-duty trucks versus passenger vehicles, and the higher cost and weight of the batteries than of conventional engines, it will likely be more challenging to electrify large trucks than light-duty vehicles.

On February 19, 2019, Columbia University’s Center on Global Energy Policy, in collaboration with the Institute of Transportation Studies at the University of California, Davis, held a workshop on the Columbia campus focused on the prospects for global truck electrification and automation and the development of new urban delivery models along with the potential energy demand impacts. Participants included experts from truck, engine, and battery manufacturers; oil companies; clean transportation NGOs; US federal government agencies and national labs; city government; the financial community; and transportation researchers from the academic community. It was conducted on a nonattribution basis under the Chatham House Rule.

The workshop focused on new urban freight delivery models\(^1\) as well as on medium\(^2\) and heavy-duty\(^3\) truck electrification and automation. It also looked at prospects for electrification in buses. There was a special focus on China given that it is one of the largest growth areas for road freight activity in the coming decades. According to the International Energy Agency, China and India will account for nearly 40 percent of the global growth in road freight activity to 2050.\(^4\) Given aggressive subsidies coupled with large scale deployment of infrastructure, China is a global leader in truck electrification and represents 50 percent of global electric truck sales today. The workshop also assessed the energy and oil demand impacts of electrification and automation in the global trucking sector. It also explored the use of hydrogen fuel cells as an alternative to battery electrification for heavy-duty vehicles. Finally, the workshop addressed the government policies that would be needed to support truck electrification.
HIGHLIGHTS

This section briefly summarizes the key insights from this workshop:

- Urban delivery trucks have a significant potential to be electrified, and a major driver will be national and city clean air policies. New models for last mile delivery, including automation, are being explored in keeping with community interest in reducing congestion and air emissions and improving safety.

- Heavy-duty / long-haul delivery trucks, which generate more than half of road freight oil demand today, will be much more difficult to electrify than the smaller trucks because of the limited range of electrified vehicles versus diesel trucks and potential cargo limits due to the weight of the batteries. They will be less challenged if battery density greatly improves or if routes are changed to a hub and spoke system that would limit the range requirements. Fuel cell trucks could be an option if the cost of fuel cell vehicles and zero emission (likely electrolytic) hydrogen is reduced and issues surrounding hydrogen storage and delivery are resolved. Development of expensive hydrogen infrastructure will likely need to precede mass marketing of trucks, which creates a chicken-or-egg problem.

- One interesting idea for dealing with range and cargo capacity in electrifying heavy-duty / long-haul trucks is supplying the power on major interstates, either with catenary wires (overhead) similar to trolleys or trains, or inductive charging, which is embedded in the road. This would allow trucks to have smaller battery packs, enough to cover the last few miles off the highway independently. These approaches would require massive infrastructure investments and present their own chicken-or-egg problems. Additional research is needed on their feasibility and costs.

- Buses are the low-hanging fruit of electrification, given their urban driving patterns, slow speeds, modest numbers of miles per day, and tendency to follow the same route and return to a centralized depot for charging at night. While they are experiencing more electric vehicle uptake than other modes today, they don't represent a substantial portion of truck oil demand and will thus have a limited impact on reducing greenhouse gas emissions. However, they provide operating experience and may help pave the way for greater electrification of other truck types. They also provide important benefits for reducing urban air pollutant emissions.

- China leads the world in vehicle electrification, with more than 50 percent of electric vehicle sales in 2018. More than 400,000 electric buses are on the roads today in China—more than 95 percent of the global total. Chinese cities increasingly restrict the entry of diesel trucks into urban centers, providing strong incentives for electrification of short-haul delivery vehicles. Long-haul trucks are unlikely to be electrified in China anytime soon, similar to elsewhere. Among the Chinese government’s goals in supporting vehicle electrification are reducing oil dependence, promoting a strategic industry of the future, cleaning the air of China’s cities, and fighting climate change.

- There was little agreement among sources cited in the workshop of the timing of full (level five, no driver) truck automation. Responses ranged from 2020 to beyond 2040. There
are contributing definitional differences on what circumstances are required to call it full automation. Differences also reflect a focus on limited, initial operation versus widespread use. Further, there was also little agreement on what form automated urban delivery would take. Will it be dual passenger/freight automated vehicles (AVs), dedicated freight vehicles, robots, or drones? Some skepticism was expressed about the latter two modes because they can carry so little relative to the volumes that need to be delivered.

- By removing the cost of the driver, fully autonomous trucks could significantly reduce shipping costs, thereby incentivizing more frequent deliveries for e-commerce (e.g., 1-2 hours versus days) and by taking market share from more fuel efficient modes of transport (rail and barge).

- Even in decarbonization scenarios, diesel is likely to remain the predominant fuel for trucks through 2040. A transition to a very low diesel-fuel world appears unlikely before at least 2050.
POLICY DRIVERS FOR GLOBAL TRUCK DECARBONIZATION

The degree to which trucks move to a lower carbon trajectory will depend on how active government policies are and the effectiveness of those policies. In addition to national policies, cities continue to feature prominently in the policy space primarily due to concerns about local air emissions and congestion.

Heavy-duty vehicles were deemed to deserve more policy attention than they have garnered in the past given emissions trends, efficiency opportunities, and prospects for zero emissions technology. While four regions already have a version of California’s Zero Emissions Vehicle policy for light-duty vehicles (California, China, Europe, and Quebec), Europe and China are considering expanding these policies to heavy-duty trucks. Heavy-duty vehicle efficiency standards are now being adopted in many major markets, and Europe is scheduled to propose the first ever heavy-duty vehicle CO₂ targets in the spring of this year. Brazil, South Korea, Mexico, and others are considering future standards.

Looking forward, each geographic area or market is likely to make its own decisions about the most attractive technologies given their climate policy, infrastructure, the electric grid, and other factors. Experts at the workshop disagreed about whether it was desirable to have the government or industry agree up front to a technology pathway for heavy-duty vehicles. While it would allow investments to be made with greater confidence and spread investment costs across higher sales volumes, it would be perilous to choose a technology while they are still evolving, and it could stifle innovation.

Addressing air pollution and climate change will require continued investments in improving diesel vehicles as well as providing cleaner fuels while there is a transition to electric vehicles. A major challenge for policy makers and business leaders is when to invest in improving environmental performance of diesel technologies and when to leapfrog to electric drive.
STATUS AND PROSPECTS FOR GLOBAL TRUCK ELECTRIFICATION

Demonstration Projects for Heavy-Duty Truck Electrification

While heavy-duty zero emissions vehicle freight demonstration projects are taking place in a number of countries today, California and Germany have a clear lead. Larger demonstration programs usually include public funding, while some are funded completely by the industry. A number of leading truck manufacturers (e.g., Cummins, BYD, Daimler, the Volkswagen Group, etc.) as well as start-ups (e.g., Tesla, Thor, Nikola, Chanje) are currently spending substantial dollars on heavy-duty truck electrification. For example, it was noted at the workshop that Daimler committed to spending $3.2 billion in its electric trucking division in 2019 alone.

Most of the demonstration programs are aimed at medium- and heavy-duty truck electrification. However, there are also demos underway of in-road and/or catenary (overhead wires) charging and medium- and heavy-duty fuel cells.

Battery Electric Truck Progress

The Tesla Semi battery electric heavy-duty truck has a 500-mile range at full load and highway speeds versus 1,000 miles for a diesel truck. However, it can go up 5 percent grade at 65 miles per hour versus a diesel truck at only 45 miles per hour. The Semi also has lower operating costs than a diesel truck ($1.26 per mile versus $1.51 per mile for diesel). A number of companies have preordered the truck (e.g., Walmart, Pepsi, UPS, DHL, Ryder, etc.).

Fuel Cell Truck Progress

The Nikola Motor Company announced that two key customers will begin fleet tests of Nikola’s zero emissions hydrogen-electric class 8 trucks by the end of this year. There are about 11,000 preorders for this truck. Nikola also plans to build 700 hydrogen fueling stations in the United States over the next seven years.

Electric Roads

Some workshop attendees were intrigued by the concept of electric roads or “E-Roads,” which supply electricity to the vehicle while it is moving, likening it to an electric train or trolley. If battery costs are excluded, then electric cars are already cheaper than conventional diesel trucks due to lower electricity prices and the relatively low cost of delivering electricity to the trucks. E-Road capital costs are generally understood, and one participant cited their research indicating that the total costs (including capital) could be competitive with diesel. Others questioned whether operating and maintenance costs were understood, given the potential for sagging wires (for catenary) or corrosion of the wires in the road, although it is not clear whether these costs would be greater than maintaining electric rail. The best solution may be developing E-Roads for major highway corridors and using a hybrid truck that can drive independently to travel the final miles to its destination. The greater the autonomy required for driving outside of E-Roads, the larger and more expensive the batteries. One participant questioned whether E-Roads were a resilient solution, given the changing climate and increased floods and storms in some locales.
NEW URBAN FREIGHT DELIVERY MODELS

E-commerce has greatly increased the number of packages being delivered globally. In the United States, the number of packages delivered annually is expected to rise from 11 billion in 2018 to 16 billion by 2020. Globally, urban freight traveled about 1 trillion miles in 2015.

Potential for Electrification

Urban delivery trucks may be a good application for electrification. These light- to medium-duty delivery trucks spend a significant portion of their trip time idling, which results in low fuel economy. They tend to have low average driving speeds, and electric motors provide higher efficiency at low speeds. The frequent deceleration and stops are also well suited to utilization of regenerative braking. And since these trucks typically operate on almost the same route every day and return to a central location at night, central recharging is feasible.

Last Mile Delivery

E-commerce has also substantially impacted supply chains with a significant share of the goods going directly to residences. That has created a problem of how to make deliveries in the last mile more efficient and profitable. The last miles on urban delivery trucks are also important to communities because of their impacts on congestion, safety, and air emissions.

Last mile delivery patterns differ depending on whether the item shipped is food, parcels, beverages, linens, or warehouse delivery (and other items). For example, parcel deliveries have a large number of stops per tour along shorter routes. Trucking companies that have large fleets will be able to incorporate different shipping needs, vehicles, and fuel technologies.

Moving to fuel choice for urban delivery vehicles, the relative cost is most impacted by the price of the vehicle and electricity versus diesel prices. Purchase voucher incentives from the government are very important as they directly affect the capital investment, whereas other use-based incentives may be minor factors. In comparing the externalities or community impacts from different types of fuels, electric vehicles have the greatest benefit. Automation may also help reduce impacts on communities by allowing deliveries to move to hours with little traffic.

Automation in Urban Delivery

Automation of urban goods delivery can take many forms:

- Dual use where autonomous vehicles (AVs) move goods as well as people on roads
- Dedicated AVs that travel on roads
- Dedicated AVs that travel on sidewalks
- Drones
Dual Use Where AVs Move Goods and People

The key driver for this mode is the time variability of passenger trip demand, which peaks in the morning, afternoon, and evening and falls precipitously in between those times. Delivering packages during the troughs allows the fleet vehicles to be fully utilized, and it also avoids congestion. A downside of this approach is that the vehicle isn’t optimized for the delivery of goods. General Motors’ Cruise and Ford are key players in this space in the United States. Cruise is starting a partnership with DoorDash to deliver meals from restaurants, and they will explore grocery deliveries. There will be a safety driver in the car.

Dedicated AV Delivery on Roads

The key driver for this mode is the ability to optimize the vehicle for fuel efficiency by keeping the weight down and to maximize the delivery of goods. The vehicle would not be subject to crash tests by US regulation if it moves at speeds of 25 miles per hour or less. These vehicles will also have limited routes, in contrast to dual-use vehicles, which reduces complexity. UDelv is a player in this space, and it has been delivering goods for Draeger’s Market since January 2018. UDelv is also working with supermarkets in Oklahoma City and an auto parts chain in Texas. It recently announced a partnership with Walmart in Surprise, Arizona. Nuro is another company operating in this space. It had been working with Kroger using more conventional AVs but added specialized AVs that are completely unmanned in December 2018.

Dedicated AVs That Travel on Sidewalks

In the United States, 40 percent of vehicle delivery trips are from retail stores and are less than two miles in length. In urban areas, that number rises to 45 percent. Thus, making all delivery vehicles capable of driving on roads may be overspecifying the vehicle specifications, given the short travel distance required. A sidewalk vehicle or robot might be appropriate for these shorter distances. A vehicle that travels on sidewalks won’t have to meet the same requirements as vehicles that travel on roads, but cities will likely have tight restrictions on anything that shares sidewalks with pedestrians. There needs to be a reallocation of curb and street space for new delivery models to work. Key players in this segment are Starship, Amazon, and Robby. Starship will have robots deliver food and drinks to George Mason University students. Trips will be monitored in real time by Starship employees using the robots’ cameras.

Drones

This delivery form has moved more slowly in the United States than in some other countries due to historical regulations about maintaining sight of the drone. There are also range limitations similar to those of the sidewalk AVs. The key players in this space are Amazon and Zipline. Amazon Prime Air launched a small drone delivery trial in the United Kingdom in December 2016, but it hasn’t been able to test it in public areas in the United States with current regulations. Zipline has a battery-powered glider designed to air-drop packages of medical supplies midflight. Earlier generations of drones have been delivering blood for transfusions in Rwanda since 2016. Zipline does not operate in the United States yet (needs permission from FAA), but it would like to start flying in rural areas of states such as Nevada and North Carolina. A company called Wing recently gained FAA approval to launch a
commercial drone service in Virginia.\textsuperscript{6}

There is currently a period of great experimentation, and it is unclear which of these new delivery models will work. One participant believed that the robots and drones may end up being niche applications because they can only hold a few parcels, which is insufficient for the volumes of packages that need to be delivered. There are also other complications associated with these applications such as rights-of-way and curbside access.

**Electrification from a City Perspective**

In New York City, passenger vehicles are responsible for 30 percent of greenhouse gas emissions, while trucks are only responsible for about 13 percent of the emissions. However, the public is much more concerned about trucks because of their idling, emissions, and motor noise and their blocking the streets when they unload. New York City has also signed on to the Paris Protocol and the mayor has an electrification target for passenger vehicles but does not yet have one for trucks. There are currently only incentives for trucks but no mandates. While it is too early to know, congestion pricing could have an incentive for clean trucks built into it. There is also an active debate about how to allocate street and parking spaces between cars and trucks.

The city has a voucher program to subsidize the private sector to replace old diesel trucks with lower emissions trucks. One recent challenge to the voucher program comes from the American requirements of federal highways specifically affecting the Congestion Mitigation and Air Quality (CMAQ) program and the need to use US-produced steel. Up until some of the “buy America” challenges for federal highways, New York City funded a substantial portion of the incremental cost of over 600 electric trucks in the Hunt’s Point area of the Bronx. Companies like DHL have taken advantage of this program. One speaker stated that it is still very early in the development of the electric truck market.

New York City is also putting in electric charging stations and fast chargers in municipal parking lots that it would allow class 5 and 6 urban delivery trucks to use. One challenge in incentivizing electrification is that most trucks in the city are leased, and the truck owners are very concerned about the end-of-life residual value of the truck. Truck owners would be hesitant to move to electric given uncertainties about battery life. Another challenge is that the small independent truckers who only own a few trucks don’t want to experiment with new technologies. A third challenge is the up-front truck capital costs and infrastructure costs as well as electric utility rate structures that aren’t supportive of electrification. Utilities talk about providing a demand charge rate reduction for seven years, but that doesn’t match the life of a truck, which is closer to 20 years. There also may be insufficient joint planning between city electrification programs and utilities. One participant thought that there needs to be more interaction with electric utilities to better understand how they can support vehicle electrification and get the pricing correct to encourage charging during off-peak hours.

The city continues to plan for the development of one fast charging location in each borough over the next year, quickly following up with a second site in each borough as they are identified. Each location will contain at least four fast chargers. Additional benefits for truck electrification can come if electric trucks qualify for a potential future Department of Transportation green curb or delivery initiative.
ELECTRIC BUSES

Electric vehicles have displaced about 3 percent of total oil consumption growth since 2011, and more than three-quarters of that oil displacement has come from electric buses, according to a new study by Bloomberg New Energy Finance. Their report estimates that “for every 1,000 electric buses on the road, 500 barrels of diesel are displaced each day.” The same number of battery-powered electric cars only displaces 15 barrels of oil a day, by comparison. To put this in perspective, it must be noted that buses use less than 5 percent of global transport energy consumption today, and they are projected to remain at 5 percent in 2040. According to Bloomberg, electric buses are expected to shave about 60,000 barrels per day off of global oil demand growth in 2019 out of total oil demand growth of 1.4 million barrels per day. Since buses are such a small share of oil demand, the main driver for bus electrification is probably improving urban air emissions and not necessarily oil demand reduction.

Most electric buses today are in China. In 2017, there were 385,000 electric buses in the world, and about 99 percent of them were in China. The city of Shenzhen alone announced in 2017 that it had completely electrified its fleet of 16,000 buses. In the United States, 10 percent of new transit orders were zero emissions buses in 2017.

Electric buses are the low-hanging fruit in electrifying heavy-duty vehicles. Diesel buses have fuel economy of about four miles per gallon, while an electric bus has an equivalent fuel efficiency of 22 to 30 miles per gallon, and electricity prices remain relatively stable in contrast with oil prices. In terms of electrifying buses versus other trucks, buses travel relatively short distances along the same routes and return to the same central depot at night. These factors facilitate vehicle charging. BYD, for example, has thus far delivered 50,000 electric buses around the world, which is greater than the 2,000 electric trucks the company has delivered.

There is also an environmental justice argument for transit authorities purchasing electric buses. Low income people are most dependent on buses, and the buses go right through their communities along with their significant air emissions if diesel fuel is used.

The technology for zero emissions buses is available today, and there is significant competition among OEMs to deliver electric buses. Often four to six OEMs will bid on local transit authority procurements when there will only be one to two bids for diesel buses. Electric buses are more expensive than compressed natural gas buses, but with a government voucher incentive, the electric buses become less expensive. Increasing scale will drive down production cost of electric buses over time.

In the United States, some skeptics have questioned whether local transit authorities can scale up the number of electric buses they purchase versus just having a handful of them. However, Shenzhen in China went from having 1,277 electric buses in 2014 to 16,359 in 2017, which represents all of their bus fleet. The largest bus fleet in the United States is in New York City, and it is roughly one-third of the size of Shenzhen’s fleet. The Innovative Clean Transit Rule in California commits all transit agencies to be all electric by 2040. Numerous transit agencies in California are expecting to beat this time frame.
Another participant questioned the performance of electric buses on hills or in extreme temperatures when heating or cooling is needed. The issue with hills and heating/cooling is not that you can’t do it but that it detracts from the range if you maintain your speed. Heating could reduce the range by up to 20 percent. Adjustments can be made to the power train, and auxiliary heaters, including heated seats, can be added to avoid range loss.

The group was interested in the potential of inductive or wireless charging and its cost and safety. The United States installed its first wireless charging system for electric buses last year with a charging capacity of 200 kW. It will be used for the Link Transit Company in Wenatchee, Washington. Within five minutes, the wireless charging system automatically adds enough energy to the vehicle’s battery to complete another route during its routine transfer station stop. There may be an opportunity for transit authorities to create the depot of the future with rows of charging plates. One expert indicated that the cost of wireless charging six years ago with a 50 kW charger was $7 per watt, and now a 250 kW charger costs $2 per watt. The US Department of Energy is providing a grant for a 450 kW charging system. Other participants raised concern about battery degradation with such a rapid charging rate. One participant indicated that a study from the US National Lab in Idaho indicated that battery degradation was not as large an issue as is commonly perceived. In terms of safety and electromagnetic issues, one expert indicated that safety of wireless charging has been tested, and it should be safe as long as a person doesn’t get between the bus (under it) and the charging plate. There are also safety standards that have to be met. The last point on wireless charging is that electric utilities will play an important role in enabling the development of charging infrastructure, and a concern was expressed that utilities are not prepared to move at the speed that transit agencies want to move. Electric utilities and Public Utility Commissions should be brought into the discussion of how to prioritize charging infrastructure projects.

There was an interesting presentation on a model that optimizes electric bus fleets and their operation. The approach was to conduct a duty-cycle simulation by considering charging power and time, braking energy regeneration, and operation feasibility. The results indicated that small batteries caused frequent recharging over larger routes and resulted in the bus missing a loop. Ultrafast charging improved operations. There wasn’t one particular configuration that is optimal, but rather a diversified fleet based on different routes makes the most sense. This model is a useful tool for optimizing bus fleet operations. You can run the model to minimize cost per mile, assuming that cost is added to the model. However, if the goal is to minimize greenhouse gas and air emissions, it might be more useful to replan routes and operations around a goal of maximizing zero emissions miles.

Finally, there was a short discussion on what battery performance characteristics have the best fit for electric buses. While there is no definitive answer, one expert indicated that they opted for battery safety and longevity. They used lithium iron phosphate batteries for buses. On long-haul trucks where range matters more, companies may be more likely to use NMC (nickel, manganese, cobalt) technology.
ELECTRIFICATION OF TRUCKS AND BUSES IN CHINA

China’s passenger vehicle sales fell by nearly 3 percent in 2018, being down for the first time in 28 years. Sales would have been down by over 7 percent if it weren’t for robust new energy vehicle (NEV) sales, which grew at 68 percent (from a small base) in 2018.

Truck sales were up by 6.9 percent in 2018 (3.2 million), including 108,000 NEVs. For buses, 400,000 were sold in 2018, with nearly a quarter of them being NEVs. Growth rates are expected to decelerate over time due to the aging population and lower economic growth rates.

Battery electric sales are mostly for micro-, light-, and medium-duty trucks. For heavy-duty trucks, battery electrics were only 0.1 percent of the sales mix in 2018. Natural gas trucks were 5 percent of the heavy-duty truck sales mix in 2018. It is more challenging to electrify heavy-duty than lighter trucks due to their longer required range and battery weight interfering with cargo-carrying capacity.

Transit buses in China are projected to be 100 percent electric by 2022 and urban trucks fully electric by 2025.

In the United States and Europe there are only two cities with populations over eight million, while China has 15 cities with populations that high. Road transport is responsible for 42 percent of China’s oil consumption, and commercial vehicles are 22 percent of transportation oil demand. Commercial deliveries are rising, given that China has become the global leader in online shopping. China is responsible for 42 percent of global e-commerce’s transaction value versus 24 percent in the United States.

The main driver of electrification in China is government policies. China’s aggressive transportation electrification policies are motivated by the following:

- Energy security and balance of trade concerns. China’s oil import dependence reached 71 percent of consumption in 2018. In the 1990s, China was more concerned about economic development and allowed its imports to rise. When oil import dependency blew through 60 percent, the balance changed and energy security became more important. Since the trade war with the United States began, China’s concern about energy security has increased, and the nation is becoming even more committed to rapidly reducing its dependence on imported oil.

- Environmental concerns, including urban air pollution and climate change. Cutting urban air pollution is a top priority of the Chinese government. Vehicles are currently the cause of 20 percent of the PM2.5 (particulate matter) in China, with diesel trucks playing a significant role in many cities. The Chinese government is also committed to meeting its targets under the Paris Agreement and responding to climate change more broadly. Some studies find that China’s electric vehicles have lower life-cycle greenhouse gas emissions than equivalent internal combustion engine vehicles today, although other research shows that, in light of China’s coal-heavy power sector, electric vehicles and internal combustion engines are about even. The International Energy Agency projects that coal will drop to 40 percent of power generation in China by 2040. Electrification will be essential to
decarbonization of China's vehicle fleet in the medium and long term.

- Industrial policy with batteries and electric vehicles viewed as strategic industries for investment. China wants to be the biggest player in battery manufacturing and is locking up supplies of critical battery metals, which the West could view as a threat.

Subsidies and policy preferences have been the driving force behind electrification. Subsidies are being phased out, and speakers were quick to point out that it was not because of US-China trade negotiations calling for them to be ended. The phaseout has been scheduled for a long time to allow the domestic industry to become more efficient and economically sustainable.

Subsidies have been critical for zero emissions bus deployment. An electric bus in China costs four times as much as a diesel bus, so government subsidies have been large to fill the gap. The range of electric buses has increased substantially in recent years (40 percent since 2015 for the smaller classes of buses). When the subsidies expire, the range is unlikely to increase further, and the ranges will be dependent on the purpose of the bus (e.g., transit, tourist, etc.).

Another policy tool is the zero emissions vehicle (ZEV) mandate. China is developing a new zero emissions credit policy for commercial vehicles, similar to its current policy for passenger vehicles.

Another major policy tool is the Blue Sky Defense initiative aimed at reducing air pollution. This initiative covers three large regions in China where 300 million people are located. All the fleets will move to zero emissions vehicles by at least 80 percent in three years. Most cities will reach the target of zero emissions vehicles by 2020, and conventional vehicles will not be able to access city centers.

While the ZEV mandate and Blue Sky Defense initiative are critical components of China's electrification policies, there is a broader policy framework in place that includes macro level policies (e.g., industrial transition, air pollution control), industrial management (administration of NEVs program), commercialization (NEV promotion in transport sector), subsidies (e.g., waiver of vehicle purchase tax for NEVs), technology innovations (e.g., national key R&D programs for NEVs), and infrastructure (developing a blueprint for charging infrastructure and installation of chargers).

Some participants said that China's electrification policies are likely to be more effective if the government correctly hands off technology development to the private sector. The market instead of the government should pick technology winners.

Although there is growing interest in fuel cells in China, especially for long-haul trucking, the Chinese government has not promoted fuel cells as strongly as it has battery electrification. Chinese industries have the potential to produce significant quantities of hydrogen, some of which could be used for vehicle fueling. These processes could lead to significant CO2 emissions, offsetting the climate benefit of displacing petroleum as a fuel. China also has some stranded renewable power that could be used to make and store hydrogen. (China's renewable power curtailment is due to delays in connecting renewable power sources to the grid, preferences given to coal plants in electricity dispatch, and the absence of economic,
least-marginal-cost dispatch rules as in many Western power markets.) However, transporting hydrogen from solar and wind farms to vehicle fueling stations would likely require construction of expensive new infrastructure.
ELECTRIFICATION AND AUTOMATION OF HEAVY-DUTY / LONG-HAUL TRUCKS

The zero emissions choices for heavy-duty trucks discussed at the workshop were battery electric, fuel cell vehicles, or putting the electricity above (catenary) or in (inductive) the road. Inductive power requires installing coils that generate an electromagnetic field in the road as well as receiving coils for electricity generation on the vehicle.

Battery Electric Trucks: Challenging Value Proposition for Customers

While they are more challenging to electrify than light- and medium-duty trucks, heavy-duty trucks are important because they are expected to be responsible for nearly half of on-road greenhouse gas emissions, and that percentage is expected to rise over time. Battery electric trucks have clear advantages versus diesel trucks in tailpipe and greenhouse gas emissions.

While the economics of electrifying heavy-duty trucks versus passenger vehicles is helped by the high fuel and maintenance cost of conventional heavy-duty vehicles, truck manufacturers need to overcome a number of challenges to electrify heavy-duty vehicles. Truck manufacturers are challenged by the relatively low volume of truck sales and the fragmented market for heavy-duty vehicles because there are fewer vehicles to spread investment costs over.

Unlike passenger cars, few firms are likely to buy a long-haul nondiesel truck unless they believe they will experience cost savings, with a short payback time, by doing so. The challenges of electrifying long-haul trucks today go beyond cost: they would significantly reduce the driving range and add substantial nonpayload weight, which takes away from cargo-carrying capacity. Charging time also needs to be reduced for battery electrics because the long idle times needed to recharge large heavy-duty batteries are costly for truck operators. Specifically, when the purchasers of long-haul trucks evaluate electric trucks, they will be concerned about these factors:

- **Range**: the travel distance per charge; range variation due to temperature and grade, load, and speed; and installed versus usable battery capacity. Customers are used to a minimum 500-mile range in diesel trucks, whereas the range in viable heavy-duty electric trucks may be closer to 250 miles. Further, many fleets run trucks 24 hours per day, seven days per week, and are not used to substantial downtime for recharging. One solution—to recharge battery trucks several times during the day—could be possible for some users, but this seems unlikely unless very fast charging options emerge.

- **Real cost of ownership**: the cost of electric versus diesel trucks, relative energy and maintenance costs, and the residual value and battery life. Up-front costs can be 100 percent more, given the current price of batteries. For longer range trucks, costs are likely to remain higher even if battery costs drop to $100/kWh, a typical target for the 2025–2030 time frame. If electricity costs are low (e.g., below $0.15 per kWh), the energy costs of these trucks should be well below diesel. Maintenance costs may also be significantly lower. These savings will help but may not be enough to offset other factors to drive demand.
- **Payload**: the weight of the electric truck versus the diesel truck, which includes electric power train and batteries, thermal systems, and auxiliaries. Long-haul class 8 trucks have a weight limit (including payload) of about 80,000 pounds and tend to max out at 40,000 pounds of payload. A diesel tractor weighing 17,000 pounds could become a 500-mile battery electric tractor weighing 27,000 pounds, i.e., 10,000 pounds more, reducing that payload by 10,000 pounds. This would likely be unacceptable for most long-haul trucking fleets. A 250-mile truck would cut that penalty in half and could perhaps be granted a few thousand pound increase in the limit, nearly eliminating the problem.

- **Charging**: the infrastructure investments required, overall charge time, maximum charging from 0 to 80 percent versus top charging from 80 to 100 percent, AC versus DC, connector, and charge levels.

- **Safety**: important to both truck manufacturers and customers.

Some participants were skeptical that battery electric vehicles would work for long-haul, heavy-duty trucks today, although it might work for medium-duty trucks and in certain applications where a lower weight load is being transported a short distance. One application that might work well today is school buses since they only operate twice a day and can recharge in between. The energy densities of batteries may well improve, which would extend the range. Another expert expressed the view that diesel is more competitive for heavy-duty trucks in 2020 in any scenario, but battery electric trucks can beat diesel trucks on a cost basis in certain geographic areas in 2040. Looking at the challenges in electrifying heavy-duty trucks helps one realize why diesel was the chosen fuel in the first place. It has high energy density and a well-developed distribution and refueling network.

It is still early days for electrification, so there are no industry standards on how to electrify yet. Also, it is likely that trucking companies need to change their delivery business model to accommodate electrification. For example, they may need to switch to a spoke and hub delivery style to reduce the range the truck needs to go before recharging at the hub. There may need to be dedicated routes in the early days to make sure the truck can charge when it needs to. There may be specific applications that lend themselves to battery electrification more than others because they have a shorter range or weight requirement (e.g., moving potato chips versus heavy equipment).

One way truck manufacturers are dealing with issues regarding the value proposition of electric trucks for customers is to codevelop the trucks with them after they have proved the concept. One truck manufacturer that participated in this workshop believed that it was possible to build a scalable product for serious production that would be profitable by 2021. Other participants were somewhat skeptical.

Certain types of regulation at this early stage were thought to potentially hinder the development of a workable product. For example, California is developing ZEV certification requirements now before the industry understands what product is possible. The certification cost will also be spread over very few vehicles.

Several additional challenges were raised by participants. There was concern about the
degradation of batteries and the impact on resale potential since the standard practice is for large long-haul players to put substantial mileage on the truck and then sell it to smaller players traveling shorter distances. Another challenge is whether truck manufacturers have the financial and human resource ability to invest in both fuel efficiency improvements for diesel trucks and electrification and automation at the same time. Both efficiency and electrification are needed to achieve climate targets, but the concern is that we may not get both.

**Fuel Cell Trucks**

The concept of fuel cell trucks using hydrogen fuel was then discussed as an alternative for battery electric heavy-duty / long-haul trucks because of their greater range and faster refueling. For the fuel cell truck to achieve zero emissions, the hydrogen fuel has to have zero emissions on a “well-to-wheels” basis. That rules out making the hydrogen from reforming natural gas. The hydrogen could be made from biogas or from electrolysis of water, either from nuclear power or surplus renewable power. One application discussed was to use these trucks for drayage to and from ports in California. The value proposition for the customer is that they can refuel in 25 minutes and have a 250-mile range per refueling. The goal is to get the recharge time down to 10 minutes, which is slightly faster than diesel.

The concept of using hydrogen as a zero emissions fuel has been around for some time, but there are some significant challenges. The cost of renewable hydrogen is too high today, as are some of the materials used in the fuel cell vehicle (e.g., platinum, titanium, and carbon fiber, which currently wraps around the tank). No technology breakthrough is expected, but costs can be reduced from scaling production up. Storing hydrogen is more challenging than storing gasoline due its higher volatility, although novel storage technologies are being worked on. There would also need to be a well-developed distribution network for delivering hydrogen. Fuel cells won’t scale up if hydrogen is not widely available at truck stops on their routes. For large-scale refueling depots (typically selling 10–20 times more fuel per day than is sold at urban fueling stations), hydrogen delivered by truck may be problematic. For a scaled-up system, delivery by pipelines will eventually be required. This represents a major infrastructure challenge. Some natural gas pipelines might be converted to carry hydrogen, but there is no agreement on how costly that conversion would be (ranges from low cost conversion to completely rebuild the pipeline and only use the right-of-way).

**E-roads**

The third option, which garnered a good deal of interest, was to have the power on the road either in catenary lines overhead or inductive charging under the road. According to the International Energy Agency, the main advantages of inductive charging include convenience due to charging being wireless, the lower risk of electrical shock, no limitations on the number of devices that can be charged, and low maintenance costs due to the lack of wear and tear of components. There is also the possibility of having both cars and trucks use this system, whereas with overhead catenaries, it seems unlikely that light-duty vehicles could be equipped to use these. However, there are also some disadvantages of inductive charging versus the use of overhead catenary lines, which include somewhat lower efficiency, higher material requirements and installation costs per lane-km, more invasive changes to the
existing infrastructure, and more complex components.\(^9\)

The main truck interstate arteries would need to be electrified, and if this were accomplished, it would allow batteries on trucks to be smaller (and lighter and cheaper, and/or the driving range could be increased). It may make sense to change the way batteries are designed and used on these trucks. Charge “on the fly” could allow a small range-extender battery to be used for “last mile” services, i.e., traveling the last 50 to 100 miles off the main highway. The cost of building electrical infrastructure up front would be high, but it was deemed to be just the sort of project the “Green New Deal” was looking for. Once the infrastructure is built, it would be relatively easy and low cost to supply power to it. The sentiment of the group was that this option may show promise and that more needs to be learned about it.

**Alternatives That Were Not Discussed**

A number of participants ruled out compressed natural gas or liquefied natural gas trucks for consideration because these sources would not get the truck to zero emissions. For example, if natural gas was the source for hydrogen as the fuel for fuel cells, you would only achieve one-third of the greenhouse gas emissions reduction from moving off diesel than if you had used a zero emissions source for the hydrogen. One participant indicated that natural gas is a competitive alternative to diesel in places like the United States that have plentiful resources and existing natural gas infrastructure. Natural gas fueled trucks won’t have the range issues of battery electric trucks because gas can be compressed or cooled to give it a higher energy density, and it won’t have as high a cost or as many infrastructure issues as fuel cell trucks. Natural gas would certainly help from an air emissions point of view. There wasn’t sufficient time to debate the role of natural gas in trucking or in a decarbonizing world, but that subject warrants further discussion.

Similarly, insufficient attention was given to the role of advanced biofuels in heavy-duty trucks. The case for biofuels is their relatively high energy densities and, for several fuels, their compatibility with existing vehicle fleets and fuel distribution infrastructure. They are still expensive to produce, and it is difficult to get production at a mass scale. Another issue with biodiesel is that there isn’t much control on the blends that are produced today, so the purchasers really don’t know what they are getting.

**Can Several Power Trains Coexist in Trucking?**

The International Energy Agency’s projections suggest that no clear winner will emerge through 2050. Instead, we will more likely see a mix of alternative power trains gaining ground in trucking over the long term. However, some participants expressed strong skepticism about the feasibility of this outcome from the truck manufacturers’ perspective. The redundancy in parallel refueling infrastructures foreseen in the IEA projection would be very inefficient. For manufacturers, developing new platforms is very costly and not highly profitable. It is usually added features that drive profitability for truck manufacturers. Having to develop multiple platforms and power trains could be very challenging for truck manufacturers, and an “all of the above” deployment of alternative power trains foreseen by the IEA would significantly undermine profitability in the sector. As one participant put it, “truck manufacturers cannot be all things to all people.” The group concluded that we may see all of these technologies in the future used for different applications (e.g., port drayage, school buses, garbage trucks, etc.).
Modeling Alternative Heavy-Duty / Long-Haul Truck Pathways

The University of California, Davis, Sustainable Transportation Pathways Program presented modeling work that compared the alternative pathways for heavy-duty / long-haul trucks in California. They looked at three scenarios:

- business-as-usual case, which is no ZEVs until after 2040;
- 80 percent ZEVs, reducing greenhouse gas emissions down to 80 percent of 2010 levels by 2050; and
- ZEVs having a 60 percent market share by 2050, with diesel biofuels blend reaching 50 percent in 2050.

Natural gas and hybrid vehicles fill in the gaps in all scenarios except for the 80 percent ZEV scenario.

Even in the 80 percent ZEV scenario (most aggressive) in 2050, diesel fuel is still nearly half of the fuel mix. Thus, one takeaway is that it will not be easy to get rid of diesel fuel, particularly since it is the most flexible and convenient alternative.

It was also interesting that program participants didn’t model any heavy-duty / long-haul battery electric trucks because they were skeptical about whether battery electrics would be successful in this space. The cost comparisons between diesel and fuel cell trucks were also interesting. In 2025, they assumed that a diesel truck would cost $140,000, while a comparable fuel cell truck would cost $200,000, or more than 40 percent more. By 2050, the costs were comparable at about $155,000. Fuel cell truck costs came down, while diesel truck costs rose due to more stringent environmental standards.

Comparing battery pack versus fuel cell costs, battery pack costs are assumed to be about $100/kWh in 2025, ultimately dropping to $70 by 2050. Fuel cell stack/system costs (measured by power, not energy) are assumed to drop from about $250/kW today to about $70/kW by 2030, and below $50 by 2050. While in both cases these technology-cost reductions will make the technologies much more competitive, they will not reach purchase-cost parity with diesel trucks before at least 2030. Thus, it will depend on fuel costs to help make the economics work. For battery trucks, electricity costs under $0.15/kWh may get the job done and lead to TCO (total cost of ownership) parity for long-distance trucks (if other obstacles such as range can be overcome). For fuel cells, zero carbon hydrogen from electrolysis would have to drop to at least $5/kg (about $5 per diesel-equivalent gallon) to have a chance for fuel savings (given the 20–25 percent efficiency advantage of fuel cells on long-haul service). This appears unlikely before a very large scale e-H2 system is established. Near-term cost estimates for electrolytic H2 are typically over $10/kg.

Automation in Long-Haul Trucking

Trucks traveled almost 116 billion miles on US interstate highways in 2015, indicating the desirability of automation corridors for long-haul trucks. Autonomous highway driving is technically far simpler than driving in cities. The idea is starting to gain momentum.
An automotive consultant participating in the workshop expressed the view that level IV autonomy is more likely to gain widespread adoption in trucking than level V autonomy (no driver). Level IV autonomy could actually be more demanding for drivers than manual driving, so legal limitations on hours driven will probably still apply and could constrain optimal fleet operations even if significant progress is made on autonomous operations.

There was no agreement about the timing of full automation. A participant from a think tank cited Daimler’s view that self-driving trucks capable of level IV automation (driver present) will be on highways within 10 years. They also cited Daimler’s view that there might be constrained platooning of trucks through 2025, with a driver in each truck until 2022, when only the lead truck would have a driver. From 2025-2027, there will likely be constrained autonomy with drivers only for pickups and drop-offs. After 2027, the truck would become fully autonomous (level V). There are also a number of start-ups in this space (Embark, Tu Simple, Ike, Kodiak, Starsky Robotics, Peloton) that have more aggressive time lines. One of these start-ups recently said that “we are confident that we will have our first commercial driverless operation in late 2020 to 2021.” Another expert view expressed was that as up-front capital costs decline, level V autonomy could come into play, but it would not be the dominant technology by 2040.

One participant expressed concern about the power requirements of automated vehicles, but the response was that special fit-for-purpose chips are being designed that will lower power requirements and the vehicles have not yet been optimized for minimizing energy use.

**Effective Government Policy**

In terms of what government policies it would take to incentivize manufacturers of heavy-duty / long-haul vehicles to become electrified and/or improve efficiency, the following ideas were generated:

- Add a third trailer to the truck to increase cargo capacity, assuming the benefits aren’t offset by hurting the truck efficiency and thus range. That would be worth further study.
- Allow the use of heavier vehicles on the road.
- Increase fuel taxes.
- Reduce excise taxes on zero emissions heavy-duty trucks.
- Reduce traffic congestion, which reduces fuel efficiency.
- Adopt technology neutral greenhouse gas emissions reduction performance standards rather than mandates that pick a technology.
- Support electrification of key transport corridors.
ENERGY DEMAND IMPACTS OF ELECTRIFICATION AND AUTOMATION IN THE GLOBAL TRUCKING SECTOR

Electrification Impacts on Energy Demand

To understand the impact of electrification on energy demand and what it would take to decarbonize the road freight sector, workshop participants reviewed the 2019 edition of BP’s Energy Outlook, the International Energy Agency’s reference and “Modern Truck” scenarios, an automotive consultant forecast, and the truck decarbonization scenario of the University of California, Davis.

Participants reviewed the transport outlook for oil demand in the 2019 edition of BP’s recently published Energy Outlook. An overarching conclusion is that the future path of oil demand is highly uncertain with a very wide range of possible trajectories.

In BP’s outlook, the demand for transportation services will roughly double through 2040, primarily due to growth in the truck fleet, especially in emerging markets. However, transport energy use merely grows about 20 percent in the case called “Evolving Transition” due to improving fuel efficiency. Fuel efficiency, electrification, and to a lesser extent, natural gas–fueled trucks will keep oil demand in check despite rapidly growing demand for transport services. Most growth in road transport is not for oil but is for electric vehicles, biofuels, and natural gas. Despite the plateauing of oil demand for road transport beyond 2020, total oil demand continues to grow for more than a decade due to growth in air travel, marine transport, and petrochemicals.

In BP’s “Rapid Transition” (deep carbonization) scenario, which is consistent with the Paris climate goals, half of global sales are for trucks using alternative fuels by 2040, but 75 percent of the fleet is still oil fueled. It takes a long time to turn over the truck fleet. The transport sector would also see relatively modest greenhouse gas emission reductions to 2040 because transport is not where the low-hanging fruit is when it comes to carbon abatement opportunities.

There are upsides as well as downside scenarios around the “Evolving Transition” scenario oil demand. Part of this is related to the global energy system’s dual challenge, namely that growing energy access could offset efforts to build a more sustainable energy system. Another reason for upside oil demand is the potential for a strong rebound effect from ride sharing and autonomous driving, which can increase transport demand significantly.

Workshop participants also reviewed the International Energy Agency’s (IEA) “Modern Truck” scenario, which lowered greenhouse gas emissions in 2050 by 75 percent versus the reference case and 60 percent below 2015 levels. In their reference case, road freight oil demand was set to grow by 5 million barrels per day by 2050 or nearly 30 percent. In the “Modern Truck” scenario, road freight oil demand was 75 percent lower than the reference case in 2050. The reduction in oil demand and greenhouse gas emissions from the reference case was driven by reduced freight activity (e.g., optimized routing and last mile efficiency), reduced load (e.g., backhauling), improved energy efficiency, a switch to biofuels and a
switch to electricity. The IEA excluded hydrogen completely, based on the assumption that hydrogen loses out to biofuels, even in a deep decarbonization scenario. The IEA sees a substantial role for biofuels in the decarbonization of trucking. One participant in our group expressed skepticism about biofuels scaling up to more than a high-cost cottage industry. That view is supported by the recent experience in the United States with advanced biofuels. Other participants suggested that more rapid transitions to alternative fuels are possible than implied by the IEA’s low-carbon scenarios.

Workshop participants also reviewed several other consultant energy demand scenarios for trucks and observed that diesel will most likely remain the dominant fuel in trucking for the foreseeable future, with diesel’s share in the trucking sector ranging between 88 percent and 95 percent in 2040 in the IEA’s baseline case. Fuel switching from diesel accounted for about 400,000 barrels per day in 2040 in the agency’s most aggressive decarbonization scenario. This consultant agreed with BP’s view that autonomous vehicles will lower the cost per mile of driving, which will incentivize additional driving and increase energy demand.

Participants also reviewed the zero emissions California truck projections of University of California, Davis. California has an 80 percent CO2 emissions reduction target for 2050. Trucks achieve only about a 60 percent ZEV sales market share in Davis’s decarbonization scenario by 2050, which is 10 years behind cars. This scenario does not meet California’s 80 percent target, but Davis is developing a new one that does. It takes about 75 percent ZEV trucks and 75 percent biofuel blends in the remaining liquid fuel to get there. Depending upon the weight class of vehicle, Davis used battery electrics, hybrids, fuel cells, natural gas, and diesel trucks in its sales mix in the 2050 scenario. Davis also showed a scenario with a larger amount of biodiesel, which tended to lower the amount of hydrogen fuel being used.

A general concern raised about all global demand forecasts is that projections of China’s trucking energy demand growth are too optimistic. China’s oil demand has been underestimated for years. But now the rapid aging of the population in China and associated slowing of economic growth may warrant a downward revision in China’s energy demand for trucks.

**Autonomous Driving Could Increase Energy Demand**

As already indicated, because they lower the cost of driving, autonomous trucks are likely to be driven more and increase energy demand. Another aspect to be considered is that level V autonomy in trucks can actually be detrimental to reducing greenhouse gas emissions due to the higher utilization and less incentive to electrify long-haul trucks. Maximizing the benefits of autonomous driving for heavy-duty / long-haul trucks requires a very large range and high utilization, which makes long-haul trucking less than ideal for electrification. This means that road transport demand can go up without the offsetting effect of electrification when it comes to greenhouse gas emissions.

**Modal Shifts Are an Underappreciated Factor in Long-Term Projections**

Shifts in market share to trucks from more fuel efficient modes of transport (e.g., rail, barge) could increase energy demand, and this is an understudied area. Such modal shifts appear to be happening in Europe but not yet in the United States.
NOTES

1. Urban delivery trucks can range from light-duty trucks and vans to medium-duty trucks.

2. Medium-duty trucks are usually defined as weight classes 4 through 7, and their weight is generally between 6 to 15 tonnes. Note that classification schemes vary across countries.

3. Heavy-duty trucks are usually defined as weight class 8, and they generally have a gross vehicle weight of more than 15 tonnes. They may also be called semis.


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