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Electric Vehicles in India

A novel approach to scale electrification.

OVER THE LAST FEW YEARS, electric vehicles (EVs) have captured the imagination of people in many parts of the world. Approximately 1.1 million passenger EVs (cars) were sold in 2017, up by about 57% from the previous years. China contributed 600,000 vehicles, the United States had 200,000 and Europe 125,000. EV sales in Norway constituted 50% of all vehicle sales. Several nations have announced that their vehicles will be fully electric by 2025, 2030, or 2040. General Motors, Ford, Toyota, Volkswagen, and others demonstrated their EV ambitions by making major EV announcements, while Chinese automakers like BAIC and Changan announced they will sell only EVs after 2025. According to Bloomberg, the global EV sales will grow by 40% in 2018. U.S. sales are expected to exceed 300,000 units, and European sales should reach around 400,000, with Germany as the leader. China will lead the way in four-wheeled vehicle as well as electric bus sales. Beijing has committed to completely switch over its taxi fleet of around 70,000 vehicles by 2020. Moreover, by the end of 2018, charging infrastructure is expected to constitute almost 700,000 stations.

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India has recognized that EVs are the future of road transportation. However, even with EVs' much higher energy efficiency and significantly fewer moving parts (and, thus, significantly higher reliability), customers often avoid purchasing EVs today only because of their higher costs. Because lithium (Li)-ion battery prices are falling rapidly, it is a matter of only a few years before EVs become a preferred vehicle in India. So far, only a lone company, Mahindra Rewa, sells a small number of cars every year. Only in 2017 did the industry and government take note that, if they failed to act, they would lose the race, and the country would be flooded with imported EVs. Besides, in most large cities, India's air quality is incredibly poor. Petrol/diesel vehicles contribute significantly to such pollution, and EVs can provide the answer.

Industry, academia, and research and design (R&D) personnel (with some government support) got together in 2017 and created a task force to figure out a solution. The group realized that EVs were being promoted all over the world with large government support and subsidies. In fact, subsidies in the United States, Europe, and China range from 30% to 40% of the total cost. However, the Indian government was not in a position to provide large subsidies, even though some tax concessions and limited incentives could have been possible. Making any significant headway in such a situation looked like an impossible task. However, the task force did not give up and persisted in finding a solution for the Indian context.

India's Unique Situation

India's vehicle composition is very different from that in many other parts of the world. Table 1 shows the annual sales of different kinds of vehicles over the last six years. It is obvious that two-wheelers dominate the Indian automobile sector (a typical traffic scenario on the road is shown in Figure 1). Three-wheeler taxis (called *autos*) operate all over India and carry a large number of passengers. The commercial vehicle segment including buses and trucks rose to 856,000 units during 2017–2018. Buses represent a

TABLE 1. Automobile sales trends (data from the Society of Indian Automobile Manufacturers).

Category	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017
Passenger vehicles	2,629,839	2,665,015	2,503,509	2,601,236	2,789,208	3,046,727
Commercial vehicles	809,499	793,211	632,851	614,948	685,704	714,232
Three-wheelers	513,281	538,290	480,085	532,626	538,208	511,658
Two-wheelers	13,409,150	13,797,185	14,806,778	15,975,561	16,455,851	17,589,511
Total	17,361,769	17,793,701	18,423,223	19,724,371	20,468,971	21,862,128

Figure 1. The typical traffic pattern on Indian roads (Sardar Patel Road, Chennai, India).

TABLE 2. Costs of passenger vehicles (four-wheelers) in India.

	Cars Sold in India (%)		
Price Range	2015–2016	2016–2017	2017–2018
Below ₹500,000	28.02	28.85	27.43
₹0.5–1 million	55.49	54.96	56.48
₹1–1.5 million	15.29	15.23	14.65
Above ₹1.5 million	1.20	0.96	1.43

Source: The sale figures and costs are compiled from the Society of Indian Automobile Manufacturers and selling market prices in India.

significant part of this total and provide public transport for a large segment of India's population. Therefore, if India could start its EV program with two-wheeled and three-wheeled public vehicles, it would make a large impact, both socially as well as in terms of the environment. City buses could follow.

The second point that needs to be understood is the low cost and affordability of such vehicles in India. Two-wheelers mostly retail between ₹40,000 and ₹100,000 (dominated by low-speed scooters with a price lower than ₹55,000). A three-wheeler auto sells for between ₹130,000 and ₹150,000 and is not affordable at higher prices. The same is the case of four-wheeled passenger vehicles. Though the number of these vehicles is also growing substantially, 28% of them cost below ₹0.5 million and 56% cost between ₹0.5 and ₹1 million. Only 16% of the vehicles are sold at a price exceeding ₹1 million (US$15,000), as shown in Table 2.

There are other ways Indian vehicles differ from those used elsewhere in the world. Most vehicles in Indian cities are driven at low speeds, averaging under 25 km/h, so the vehicles have to be designed to be energy efficient at such speeds. Furthermore, they rarely travel long distances. A privately owned two-wheeler would typically travel 20–30 km, and a four-wheeler would travel about 30–40 km/day. Besides, the ambient temperature in most parts of the country is over 35 °C and can exceed 45 °C on many days. One needs to understand the impact of these temperatures on the life cycles of EV batteries when they are being charged as well as discharged.

EV charging infrastructure is a major expense everywhere in the world. Who would build such an expensive infrastructure in India, especially because it is unlikely to financially break even for a long time to come? In India, interest rates on capital hover over 10%, making it difficult to invest and receive returns over the long run.

Most importantly, because India's EV program will get no subsidy (or only a very limited one), the country needs to determine how its EV strategy can evlove so that it will not require a substantial financial subsidy from the government.

It was clear to the task force that it must evolve an approach different from that adopted elsewhere and consider India's uniqueness as a strength. Stakeholders must be courageous in the ways they innovate and come up with approaches that make commercial sense in India today.

India's Strategy

Given the constraints/opportunities discussed previously, India's EV strategy evolved by focusing on

1) the energy efficiency of EVs

2) adding battery swapping as an option to charging and developing a charging and swapping infrastructure
3) an end-to-end battery ecosystem from materials to battery pack
4) the generation of demand, especially with electric public transport.

The strategy resulted in a unique approach for India's EV ramp-up. We will illustrate this with an example of an electric auto widely used for public transport.

Energy Efficiency Enhancement

The focus was to minimize the use of energy (watt-hours) per kilometer of travel. A typical electric three-wheeler auto [like the one shown in Figure 2(a)] consumed 80 Wh/km on Indian roads in early 2017. Because this was considered excessive, a goal was established to reduce consumption to 45 Wh/km. It then appeared to be an impossible task. Brushless dc electric motors or switched reluctance motors were designed to replace induction motors. Tires were improved to lower rolling resistance, and attempts were made to reduce the weight of the vehicle. Finally, creating better vehicle aerodynamics helped in enhancing energy efficiency.

Over the last ten months, most auto manufacturers have reduced their products' energy consumption to below 52 Wh/km. The 35% reduction in energy usage means that the battery size required to travel a certain distance decreases by 35%. Because the battery dominates the costs of the EV, this reduction is substantial, cutting the subsidy required. More can be accomplished in the future. Distributed motors will be one way to go. The strategy of enhancing energy efficiency is paying dividends in all kinds of EVs. In the case of city buses, the energy requirement has been reduced by 40%.

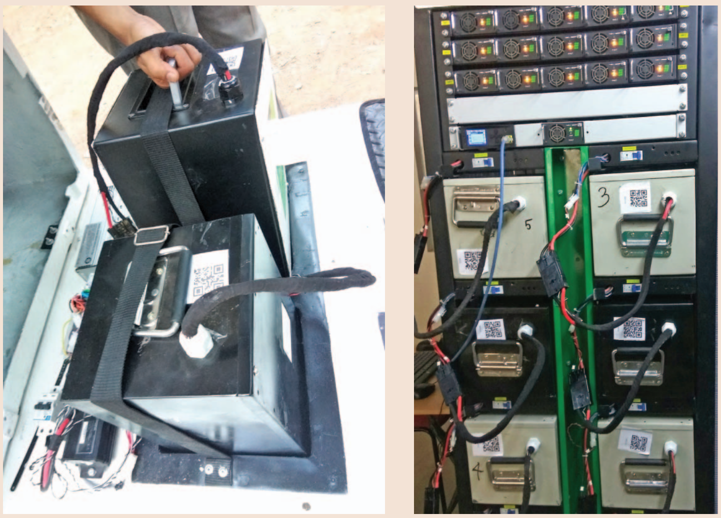
(a)

(b)

Figure 2. (a) An electric auto (the most widely used example of a general three-wheeler) and (b) an electric rickshaw.

Battery-Swapping Options

Even though enhanced energy efficiency brought the vehicle's capital cost down, some subsidy was still required if EVs were to compete with petrol-based autos. The cost for a battery that provides a desirable range would still be substantial. What if one used a much smaller battery size, say, a third of what would provide an acceptable range? This requires fast-charging several times in a day, and the low-cost batteries used could not be charged fully in less than an hour. Waiting an hour for batteries to charge is unacceptable. What if one could simply swap the discharged battery with a charged one? Figure 3 presents the easy swapping mechanism developed for a three-wheeler and an example of chargers used for such three-wheeler batteries. The waiting



(a) (b)

Figure 3. The swapping of batteries with (a) one of the batteries being taken out of a three-wheeler and (b) a charger used for these modular, swappable small batteries.

time would now decrease to a few minutes—quite acceptable to the auto driver. The engineering challenges involved in handling and fastening batteries and using appropriate long-life connectors were addressed. One big advantage is that batteries no longer need to be fast-charged in the vehicle, especially at high ambient temperatures. The vehicle could be ready to leave within minutes. The swapped-out battery can be taken to a conditioned indoor environment and charged in about 2 h. This would preserve the life cycles of even low-cost battery chemistries. The batteries would no longer be sold with the vehicles; instead, a separate business, referred to as an *energy operator* (*EO*), would purchase the battery, charge it, and lease it to a vehicle at different outlets. An EO would have to set up a large number of swapping stations so that a vehicle could easily access one when needed.

For an EO's battery-swapping venture to be successful, it is desirable that a common battery be used in different manufacturers' autos. The automobile manufacturers in India got together and determined this common battery, confining themselves to the establishment of battery energy capacity (in kWh) and minimum number of life cycles as well as the maximum size and the maximum weight. These manufacturers also defined the connector and the communication protocols the battery will use to talk to a vehicle and to a charger, but they left the chemistry to the battery manufacturers. Thus, as newer chemistries emerge, batteries incorporating these can be used. While this description is for battery swapping in a three-wheeler, it also works for buses, two-wheelers (e-scooters), and four-wheelers (passenger vehicles), as discussed later.

Hitherto, it was understood that the charging infrastructure is a precondition for EVs to work, but battery swapping adds a new dimension. Because battery swapping is economically viable, businesses can set up battery swapping and the required battery-charging infrastructure. This would enable EV usage to take off. Vehicle charging can then be added by the same business that sets up the battery-swapping infrastructure based on requirements. The difficult problem of setting up charging infrastructure is largely resolved.

Digitalization of the Battery-Swapping Operation

The battery-swapping operation, involving charging and swapping, payment for different services, and performance monitoring, is quite complex. This is simplified by the digitalization of the whole process, assisted by mobile telephony. The EO would charge for the leased battery based on kilowatt-hour usage and the term of the battery's lease. It is important that customers not be able to charge the swappable battery themselves and, instead, would return it as soon as it is significantly discharged. To ensure this, locked smart batteries were designed. Such a battery cannot be charged except by an EO-authorized charger and can be discharged only by the vehicle for which it is leased. This is accomplished by disconnecting the battery from the terminals/connectors internally and allowing a communication protocol to be on only at the beginning. The battery first communicates with the authorized charger or vehicle, and encrypted tokens are passed for authentication (similar to a blockchain). Upon authentication, the battery is connected to its terminals, allowing the input and output of energy.

> ***It is important that customers not be able to charge the swappable battery themselves and, instead, would return it as soon as it is significantly discharged.***

Furthermore, the battery communicates with the vehicle controller and stores (in its battery management system) complete data about vehicle usage, including speed and acceleration every second and the amount of energy used. It also stores information concerning the battery's state of charge, the state of balance of cells, and the temperature of each cell. A vehicle-to-battery protocol is defined to enable this as well as the authentication. Similarly, a battery-to-charger communication protocol is defined. After authentication, the charger picks up all the stored information from the battery and sends it to the cloud. While charging the battery, it also receives information on cell balance, cell voltage, and currents and temperature. There is an option of adding a global positioning system to the vehicle and recording the positioning information in the cloud. All these data are then processed to determine an individual's driving habits, the vehicle's performance (especially its energy efficiency), and the battery behavior during charging and discharging. The latter will help to ensure that the battery is used optimally and has a long life.

The careful design of the battery-swapping and communication protocols ensures that the battery-swapping business becomes viable. At the same time, the user benefits in comparison to using a petrol vehicle.

Battery Ecosystem

The battery is the key subsystem that makes EV use possible and dominates the cost of EVs. A nation cannot transverse to full electric mobility without building a sound battery ecosystem. India's low affordability implies that it should choose the lowest-cost battery. Table 3 provides different Li-ion battery options available today. Note that Li cobalt oxide ($LiCoO_2$)/graphite, nickel cobalt aluminum oxide (NCA)/graphite, and nickel manganese cobalt (NMC)/graphite are not only the lowest-cost options, but they have the highest specific energy in terms of watt-hour per kilogram. This makes them the lightest among the Li-ion cells. These cells, however, have moderate cycles unless silica is added to the graphite anode. Others used ceramic separators to enhance the number of life cycles. It is expected that some variations of these chemistries are likely to have specific energy in excess of 400 Wh/kg and cell costs of about US$80/kWh in the future.

The other drawback for these cells is their poor high-temperature behavior and safety aspects. Careful thermal design and the design of a battery management system needs to address these weaknesses. An alternative is NMC/lithium titnate (LiTO), which has excellent life cycles, can withstand high temperatures, and is safe. The problem of these cells is the weight and cost. Unless the battery used is very small and charged very frequently, the NMC/LiTO option is not attractive.

The lithium iron phosphate (LiFP) cells fall in between. They have a moderate cost, even though they are safer and have slightly higher life cycles than NMC. However, the cells have a theoretical limit of 160 Wh/kg for their specific energy. China has set a target for all EVs to have 350 Wh/kg by 2020, 400 Wh/kg by 2025, and 500 Wh/kg by 2030 (China Association of Automobile Manufacturers, Beijing). Most of the world uses NMC/graphite, and the future in the near term clearly suggests NMC/graphite.

Therefore, India opted for NMC/graphite as the cell of choice and went on to build the battery ecosystem. This ecosystem includes making battery packs using the cells (30%–35% added value), cell manufacturing (25%–30% added value), and securing materials and chemicals (about 40%–45% added value). Over the last couple of years, India has mastered

- cell-to-pack manufacturing involving quality thermal design to ensure that packs will work in Indian temperature conditions quality mechanical design ensuring that each cell has the right pressure a battery management system ensuring balanced charging and discharging of cells and guaranteeing that no cell has thermal runaway.

The country has begun to recycle existing batteries, mastering recovery of 90%–95% of such materials from used batteries in an environmentally friendly manner with zero effluents.

India does not have the technology to manufacture commercial Li-ion battery cells that can compete with the rest of the world's. The approach here is to invite international companies that have the best cells. The most complex part is getting the materials. India does not have the resources needed. Therefore, the country has begun to recycle existing batteries, mastering recovery of 90%–95% of such materials from used batteries in an environmentally friendly manner with zero effluents. The task force recognized that India's Li-ion battery material strategy must be based on such urban mining.

Demand Generation Strategy

The final aspect of India's EV strategy focused on creating some early demand for vehicles and subsystems so that the EV industry could grow. The demand generation strategy the task force determined is based on public vehicles. The task force would work with the government to create quantity requirements for three-wheelers, four-wheel taxis, and public intracity buses. At the same time, it would persuade the government offices to start using only EVs. This early demand generation is spurring the industry to move forward rapidly. Table 4 provides the industry ecosystem that has emerged for EVs over the last year.

Electric Autos

As discussed in the sections "Energy Efficiency Enhancement" and "Battery-Swapping Options," the auto is a low-cost taxi, used widely not only in big cities but also in most of India's small towns. The vehicle could easily be

TABLE 3. The battery cell options available today.

Li-Ion Cell Chemistry	$LiCoO_2$/Graphite or NCA/Graphite	NMC/Graphite	LiFP/Graphite	NMC/LiTO	LiFP/LiTO (Niobium Doped)
Specific energy (Wh/kg)	150–300	150–300	90–120 (150 with silica in anode)	60–100	50–80
Charge/discharge rate	0.5C/1C	1C/1C (2C with silica in anode)	1C/2C (4C with silica in anode)	4C/4C	5C/10C
Life cycles	1,000	2,000 (8,000 with silica)	3,000 (4,000 with silica)	10,000	20,000
Safety	Cell < 55 °C	Cell < 55 °C	Safer	Safest	Safest
Cell costs/kWh	US$120	US$145	US$225	US$500	High

The C-rate is a measure of the rate at which the battery is charged/discharged relative to its maximum capacity.

TABLE 4. Some industries that have committed to scaling EVs and EV subsystems manufacturing and services in India.

EVs:	Ashok Leyland, Tata Motors, Mahindra Electric, Eicher, Bajaj, Kinetic, Lohia, Electrotherm, Goenka, Hero-Eco, Okinawa, Ather, Avon Cycles, TVS Motors, and Mahindra and Mahindra
Li-ion battery and recycling:	Exide, Amar Raja, Exicom, ACME, Grintech, Greenfuel, Ion Batteries, Attero, and Sun Mobility
EOs:	Essel Infra, Sun mobility, BPCL, NTPC, PGCIL, and Kerala DISCOM
Chargers and motors:	Exicom, TVS Motors, Consulneowatt, Valeo, Compageautomation, most state governments, and state transport units

BPCL: Bharat Petroleum Corporation Ltd.; NTPC: National Thermal Power Corporation Ltd.; PGCIL: Power Grid Corporation of India Ltd.

(a) (b) (c)

Figure 4. Passenger vehicles in rural India (a village near Red Hills, Chennai, India). (a) A rural Indian three-wheeler bike and (b) and (c) tractors being used to transport people and materials.

Figure 5. An overloaded bus on an Indian road (Adyar, Chennai, India).

converted to electric, but, when used with a sufficient-sized Li-ion battery, the capital cost is too high. The task force met with a group of auto manufacturers to work together on

1) enhancing the vehicles' energy efficiency from 80 to 52 Wh/km
2) defining a common and smaller battery to provide a minimum range of 50 km.

The autos were sold without a battery at a cost similar to that of petrol autos. The batteries would be purchased by an EO, who would set up charging and swapping stations and lease the batteries. The ecosystem is ready to scale.

E-rickshaws (like the one shown in Figure 2) are low-speed versions of e-autos. Wider-body autos are used extensively in rural areas (as in Figure 4) and carry a larger number of passengers. Cargo autos are used to carry goods within cities. They can all be electrified using the approach described previously. Making them energy efficient and defining standard batteries would be the key.

Electric Buses

The 9- and 12-m buses are used extensively in most of India's large cities to carry intercity traffic. A typical bus route is in about 25–30 km. Because of high-traffic routes, most of these buses move slowly (averaging 15 km/h making about eight to ten trips per day). India is adopting a novel approach to electrify such buses. First, the energy efficiency buses are enhanced from 1,600 Wh/km to about 950 Wh/km when air conditioning is not used. Next, to keep the costs low, a battery of 55 kWh was standardized. This ensures a 35-km travel distance even when air conditioning is used and the battery is near the end of life. This battery is swapped at both ends of the journey (see https://www.youtube.com/watch?v=8ibDFMa4JMA). A consequence of this is that the battery weight is only about 600 kg. The lower weight means that the bus can carry more, which is important in a country like India, where buses are often overloaded (as shown in Figure 5).

India opted for NMC/graphite as the cell of choice and went on to build the battery ecosystem.

Personal Vehicles (Two-Wheelers and Four-Wheelers)

As discussed so far, the use of battery swapping in addition to fast-charging has given a new boost to EV use in India. But how does one make personal vehicles economically viable in the absence of a subsidy? The task force has come up with a unique strategy.

It is illustrated with a low-cost petrol car costing about ₹400,000. If this vehicle is redesigned as an EV with a low-cost NMC/graphite battery of, say, 100-km range, it should be possible to sell it at ₹475,000. However, if a battery with a 200-km range is used, the cost would reach ₹650,000, making it too expensive for those. Thus, a 100-km vehicle range is the only option. Now, typical users of such a car drive under 100 km 90%–95% of the time. On those days, overnight charging of the vehicle is adequate. The difficulty is the other 5%–10% of days. The user must find an available fast-charger in the daytime and wait there for an hour to charge the vehicle. This wait is not acceptable, and so the user may not switch from a petrol vehicle to an EV. The attempt to charge faster will also severely impact the life of the low-cost battery.

So what is the option? What if the vehicle is designed to have two compartments, each with a capacity for a 100-km-range battery: one compartment containing the fixed battery and the second left empty. On 90%–95% of days, overnight charging of the fixed battery is sufficient. On the day the user needs to travel a longer distance, he or she drives to a petrol station that provides charged 100-km-range batteries, referred to as *range extension* (*RE*) batteries. Such a battery could be mounted on the vehicle in about 4 min, and the vehicle would then have an additional 100-km range. If a vehicle needs to travel even further than 200 km, the used RE battery could be swapped at another petrol station, extending the range to 300 km. The vehicle can go on and on by further swapping when needed. There is no range limitation, and fast-charging infrastructure is not even required. But, if fast-charging infrastructure is available, then the user would have an option of either fast-charging batteries (waiting for an hour) or swapping.

The same approach can be used with two-wheelers. E-scooter manufacturers have gotten together and defined a standard RE battery. The e-scooter has slots for two batteries. One is fixed, typically providing a 50-km range, and the RE battery (with another 50-km range) is swapped in when required. These vehicles are being tested today and will soon be launched into the market. Because two-wheelers dominate the Indian auto market, the switch over to electric is expected to happen rapidly.

Conclusion

As discussed in this article, India has chosen to take a novel approach for its EV program, recognizing that EVs are important but also considering the obstacles of low affordability and lack of a large government subsidy. Its approach to EVs will, therefore, not be consonant with that in the rest of the world. Thus, battery swapping has been added to public charging. Users no longer have to wait for expensive charging infrastructure to be built. Businesses would set up a battery-swapping infrastructure because it would make economic sense. They will add appropriate public slow- and fast-charging, where there is a demand. India has decided to carry out urban mining to secure battery materials. It recognizes that the higher efficiency of drivetrains brings down the cost of an EV. It needs to carry out R&D to develop the most efficient electric drivetrain including innovative motor and controller design and other power-electronic subsystems. India's approach is more in tune with India's economy. Its large market gives it a chance to establish this alternate approach. The approach may be useful not just to India but probably to 70% of the world, where similar affordability exists. Only time will tell.

For Further Reading

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