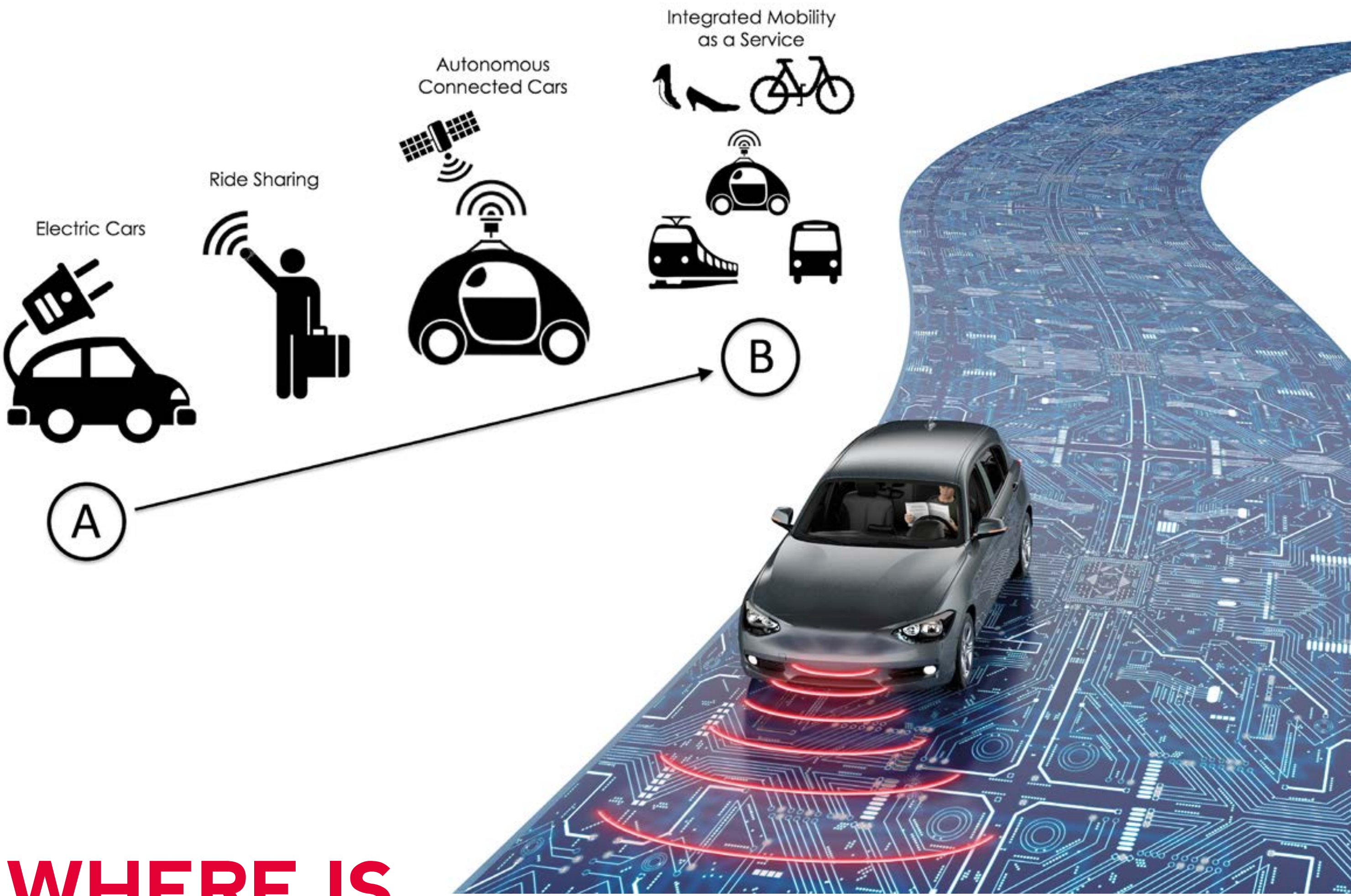

WHERE IS TRANSPORTATION GOING?

George Crabtree[1], Elizabeth Kocs[2] and Bryan Tillman[3] – DOI: https://doi.org/10.1051/epn/2017303
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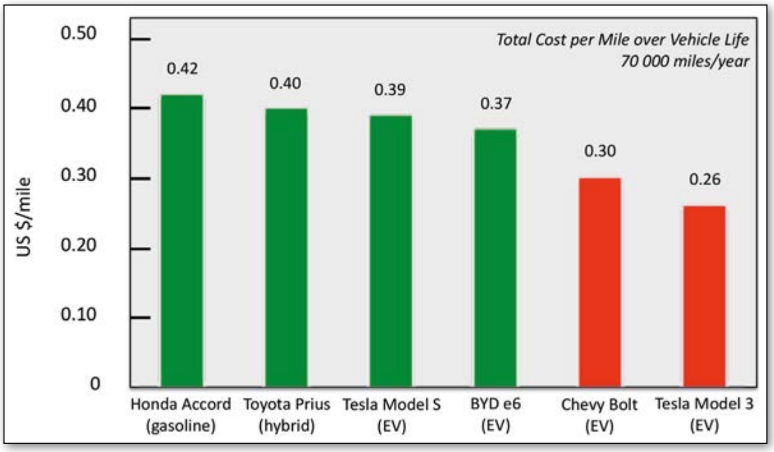
The Roman Empire introduced roads and transportation to promote culture, business and growth. It's time for the next step.

Disruptive innovation often occurs via the convergence of several creative advances. The smart phone, for example, arose from the emergence of lightweight lithium-ion batteries, Moore's Law in digital electronics and cell phone towers for wireless communication. Transportation is ready for such a disruptive leap, arising from electric vehicles, charging/electrical infrastructure, ride sharing, self-driving cars, and big data. The technology for these advances is already in place; completing the transformation requires only their integration into new paradigms for mobility and public acceptance by consumers and businesses.

Electric vehicles are the technological foundation of the new mobility. The price of batteries has declined dramatically in the last decade [1, 2] and continues to fall faster than expected (see Box). This and the learning curve for manufacturing electric cars has decreased the purchase price of electric vehicles from approximately $100k in 2008 to $35k in 2017 for a car with 200-mile (300 km) range. The operating costs of electric cars are significantly lower than for gasoline cars – driving a mile on electricity costs about half as much as driving on gasoline – and electric motors have a single moving part, the rotor, compared to hundreds of moving parts in a gasoline engine. Fewer moving parts dramatically reduces maintenance

▲ In twenty years, the technology, practice and business model of transportation will evolve from personal car ownership to mobility as a service, combining several modes of transportation for a single trip (Source: authors + ©iStockphoto))



▲ **FIG. 1: The lower fuel and maintenance costs of electric vehicles more than make up for their higher purchase price if the cars are driven 70 000 miles annually, as is typical of taxi and ride-sharing fleets. (Source: Vehicle Electrification Economics, Rocky Mountain Institute, October 13, 2015)**

costs while increasing longevity. For high-mileage cars, such as taxis and ridesharing vehicles, the total purchase plus operating cost of electric cars is already significantly cheaper than gasoline cars, as shown in Fig. 1 [3].

Ride sharing provides the mechanism for exploiting the low cost of high-mileage electric cars. The average personally owned car is vastly underused – parked about 95% of the time at home or at work, providing mobility only 5% of the time and usually carrying only a single occupant, the driver. Personally owned vehicles are driven 12 000 – 15 000 miles annually, compared to 70 000 miles for the average taxi. The dramatic rise of ride sharing services such as Uber and Lyft threatens to create a "new normal", replacing many low-mileage, underutilized personally owned cars with a few highly utilized, high-mileage fleet cars [4]. These cars will be overwhelmingly electric, taking advantage of the lower operating and maintenance costs of electric vehicles.

▼ **FIG. 2: Parking cars and trucks in urban areas is time consuming, expensive and requires precious land that could be devoted to more productive uses. (Source: public domain)**

Ride sharing eliminates parking, an expensive and time consuming necessity for personally owned vehicles, and frees land in urban areas devoted to parking lots and garages for more productive uses (Fig. 2). Ride sharing also increases traveler flexibility, allowing seamless connection with other cost-effective and convenient mobility options such as walking, biking and public transit.

Self-driving cars are the next cog in the mobility transformation. Self-driving had its humble origins in electronic cruise control in the 1970s, and has grown steadily since to take over more and more driving functions as sensors and digital decision making matured, as shown in Fig. 3. Autonomous parallel parking is now widely available [5] removing the stress from this famously tricky maneuver. Many self-driving buses are now in place in restricted environments such as corporate campuses and private parks [6, 7] and far more sophisticated driving function is now within technological reach [8]. Google, Tesla, Toyota, Bosch, BMW and Daimler now have several million miles of experience with self-driving cars; they and others are racing to commercialize self-driving hardware and software [9]. The US has issued a set of proposed federal guidelines for self-driving vehicles; Europe and Japan are preparing similar international standards. The revised version of these guidelines will become the first self-driving rules of the road. Pittsburgh and Singapore have rolled out fleets of self-driving ride share cars on public streets [10]; these pilot programs are ready for replication, with refinement, in other cities.

Big data promises an even grander mobility transition. As revolutionary as self-driving is, it is only the near edge of the autonomous vehicle horizon. We can easily equip every car with a global positioning system (GPS) that reports its location, speed and direction, and this information can be collected wirelessly in a "transportation cloud". Such a data base empowers connected vehicles that share congestion, weather and road construction information and communicate recommended driving behaviour to autonomous or human-driven cars to minimize traffic, speed travel times, and reduce traffic accidents. This level of coordination is well within reach of big-data software using known methods.

Benefits

The new mobility brings far more benefit to the individual driver than simply being freed from making driving decisions. Statistical learning can predict when to make a given trip to encounter minimal congestion, re-route in real time to accommodate last minute itinerary changes and reduce delays, and adjust driving style for weather conditions such as rain, snow or slippery roads. At-risk groups such as the elderly, people with disabilities, and

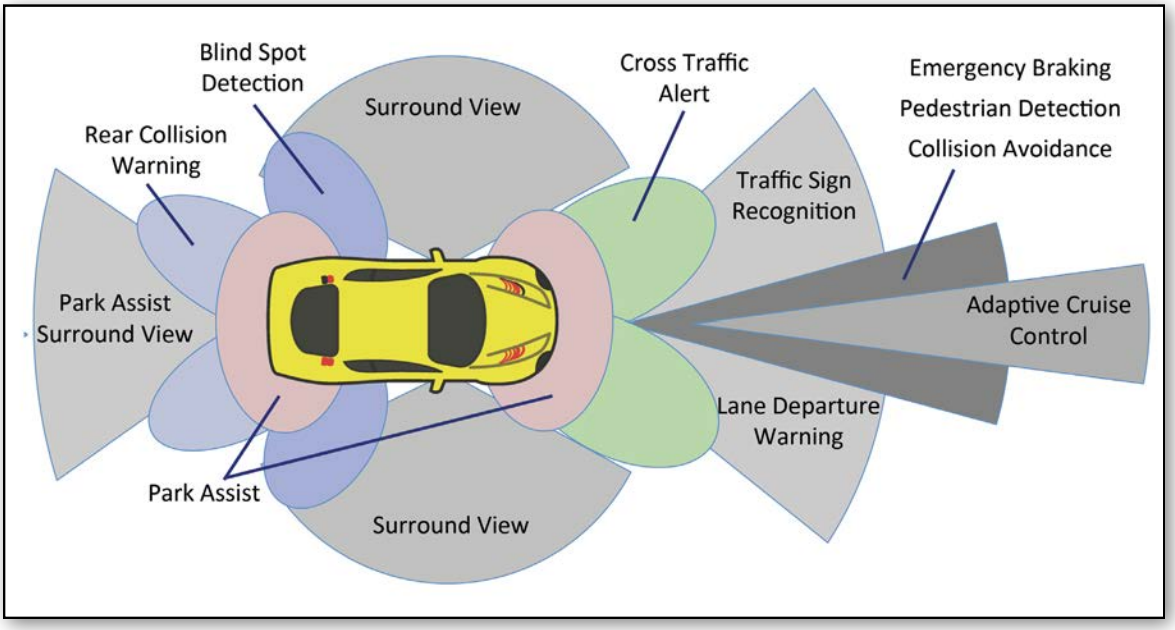


FIG. 3: Self-driving cars "see" lane markings, pedestrians, bikes, other vehicles, and objects in their path with many kinds of sensors. (Source: Authors)

children will have more mobility options and increased social well-being [11].

On the societal level, self-driving cars eliminate driver error, a major cause of accidents. Machines do not get tired, become distracted by texting, phone calls or in-car conversations, and they do not drive while physically impaired. The economic cost of traffic accidents is enormous - over $240B directly and over $800B in total harm in the US, according to the US National Highway Traffic Safety Administration. Fewer accidents mean lower medical costs, lower insurance rates and higher productivity through lower travel times. Sophisticated crash avoidance systems are already seeing lower insurance premiums, a trend that will accelerate as self-driving matures. Freight transport may see larger benefits than personal transport, including reduction in the number of drivers and rest stops on long hauls and the aerodynamic benefits of platooning, as shown in Fig. 4.

Self-driving vehicles increase the capacity of our surface transportation network for people and freight. Reducing congestion increases economic efficiency, and rolling out electric vehicle infrastructure such as fast charging stations and connected autonomous vehicles creates jobs and promotes economic growth.

Public health will see significant benefits from the new mobility. In dense urban areas tailpipe emissions from gasoline vehicles affect large numbers of people, while electricity generation is located away from cities where its pollution reaches far fewer people. The conversion of coal generation to gas and renewable wind and solar means that grid electricity gets cleaner every year, while the pollution of gasoline cars remains unchanged over the life of the car, a decade or more. Electric vehicles are a remarkably effective route to fewer lost workdays due to pollution-related illnesses, fewer asthma attacks, and fewer premature deaths.

Implementation

One of the beauties of the new mobility is that it can be implemented in stages. We are already seeing significant numbers of electric cars on the road, the charging infrastructure to support them, and a growing proliferation of ride-sharing services. Self-driving cars are rapidly approaching early adopter status, and vehicle connectivity via in-car GPS is a natural extension of the fusion of information and driving, as shown in Fig. 5. Each of these advances is within technological and economic reach; each brings mobility advantages, and their combination brings benefits well beyond the sum of the parts.

Imagine the year 2035, where transportation has adopted the technological, societal and generational trends that are now maturing [12]. Mobility is a service, less about car ownership as a personal statement and more about convenience and utility. The sharing economy allows open access and greater choice to riders and drivers, and financial benefit to both. The cloud and statistical learning personalize your daily mobility needs. Cities accommodate people at higher density with higher efficiency, less congestion and space devoted to parking. Emerging millennial culture becomes a dominant theme.

In less than twenty years, transportation will be transformed, in large part due to improved technology, both

FIG. 4: Self-driving vehicles can platoon, following each other much more closely than human drivers can do. Platooning reduces aerodynamic drag, uses road space efficiently, and allows flexible convoy configuration. Platooning applies equally well to cars as to trucks. (Source: Institut fur Kraftfahrzeuge (ika), RWTH Aachen University)

incrementally and disruptively, and at the same time, cars and the business models that support them will evolve to meet the demands of future users [13].

Is a future like this so far-fetched? Autopilot was developed in 1912 and remains a staple for airline pilots and maritime captains. Sales of unmanned military aircraft and commercial drones are rapidly outnumbering piloted airplanes. Automation is increasingly utilized for safety, precision and efficiency including robotic surgery since the mid-1980's, and automated industrial machinery since the mid-1940s. Although we don't know exactly what the future holds for transportation, we do know that technology, connectedness, the Internet and evolving societal expectations will dramatically transform its character. ■

Acknowledgement

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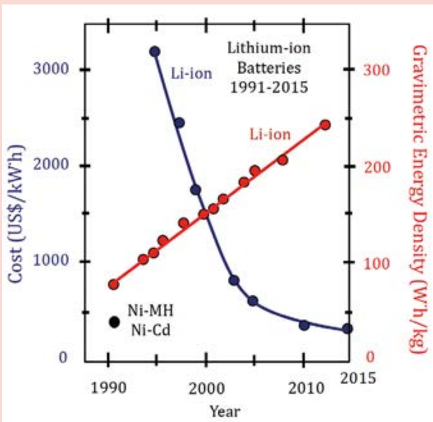
BOX: BATTERIES AT THE THRESHOLD

The battery is the dominant feature of electric vehicles. Its energy determines driving range, its power determines charging time and acceleration, its mass determines the energy required for driving, and its cost determines the price of the car. The ultimate success of electric cars depends on how much better batteries can become and how soon they can get there.

Dramatic improvements in the performance and cost of lithium-ion batteries (see figure) drove the personal electronics revolution. At their launch in 1991, lithium-ion batteries beat the next best batteries by a factor of two in gravimetric energy density (Wh/kg), and continued to improve steadily over the next 25 years by another factor of three. This factor of six in energy density enabled portable laptops, tablets and smart phones – imagine how limited, and less popular, these devices would be if they were six times larger and six times heavier. The cost reduction of lithium-ion batteries has been even more impressive than their performance increase, coming down more than a factor of ten since launch, and continuing to fall each year faster than projected.

Batteries for electric cars have more stringent criteria for mass-market acceptance than batteries for personal electronics. The batteries must be much larger to achieve acceptable driving range, much cheaper to make electric cars widely affordable, much faster charging to compete with gasoline car refueling, much longer lasting to match the lifetime of a car and much lighter to reduce the energy required for driving. Of these requirements, cost is the least challenging. As the figure shows, cost improves much faster than performance, and can be further reduced by improvements in manufacturing, such as those in gigafactories that promise to lower cost by an additional 30%. In contrast, the challenges of charging time, lifetime and weight reduction require fundamental science and technology advances in battery design that are beyond manufacturing and will be harder and slower to achieve.



▲ At their launch in 1991, lithium-ion batteries had twice the gravimetric energy density of Ni-metal hydride and Ni-Cd batteries, the best available at the time, and their energy density has improved an additional factor of three since. Cost has fallen even more impressively, by more than a factor of ten, and continues to decrease each year faster than projected. (Figure adapted with permission from (2).)

Will lithium-ion batteries drive a transformation of mobility from gasoline to electric vehicles comparable to the personal electronics revolution? It seems clear that lithium-ion electric vehicles are here to stay and will compete with gasoline vehicles in high-mileage applications. For electric cars to replace gasoline cars across the board the way smart phones displaced land phones may require the next generation battery whose performance is several times better than lithium-ion, just as the performance of lithium-ion batteries is now several times better than its predecessors.

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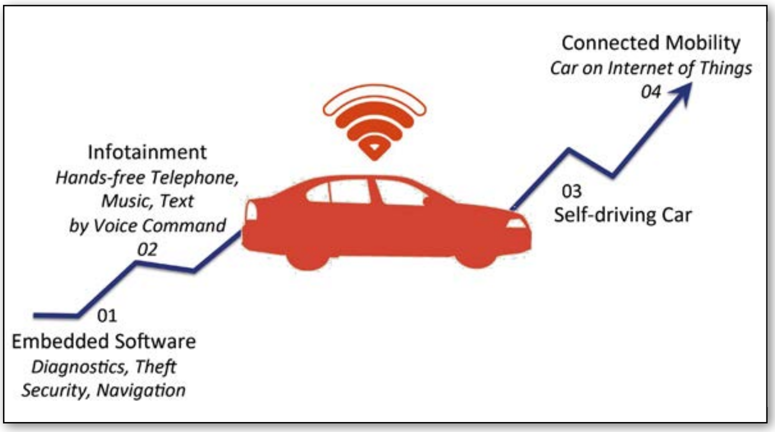

▲ **FIG. 5:** The evolution of the connected car, incorporating information into the driving experience in increasingly sophisticated ways. (Source: Authors).

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[Letter to the Editors]

Dear Editors,

In europhysicsnews 48/1, 2017, I read on page 30 that "nuclear energy is currently the only ready to use large-scale backup option for power production in an environment that is increasingly dominated by intermittent wind and solar power production". I consider this statement a political statement, not a scientific one, and I therefore dislike it.

History has taught us with Kytshtym (1957), Windscale (1957), Harrisburg (1979), Chernobyl (1986), Sellafield (2005), and Fukushima (2013) that nuclear power is no honest "option" if we hope for a long-time (centuries) survival of mankind on this planet. When you consult the internet concerning "Fukushima", you learn what I mean.

So why does "solar power" need a "backup option"? In Germany, during the 1980s, our president of the physical society Werner Buckel tried to convert us from nuclear to solar, but failed for political reasons: the Sahara was not considered a politically safe region.

Rudolf Kippenhahn, in his 1990 book "Der Stern, von dem wir leben", proved its feasibility on page 297. Similar words were expressed by our top physicist Freeman Dyson in 1999, in his monograph "The Sun, the Genome, and the Internet",on page 67. And an even more quantitative feasibility proof was published in Scientific American in December 2005 on pp.84-91, by William H. Hannum, Gerald E. Marsh, and George S. Stanford. Yet more recently, in 2013, Christoph Buchal, Patrick Wittenberg, and Dieter Oesterwind published 115 practical pages for German speaking people under the title "STROM".

We need no "backup option", I conclude, if we like life on Earth.■

Wolfgang Kundt, Bonn University.