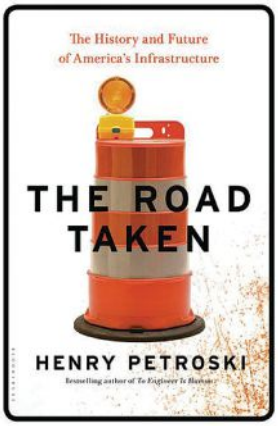
The Road (Not)Taken

Tau Bate, engineer and historian Henry Petroski, Ph.D., P.E., has written *The Road Taken,* a critical look at the history and future of America's Infrastructure. We reprint here the final chapter, titled "Ages and Ages Hence"



The future promises to bring us smart cars riding along smart highways and over smart bridges. Even if the drivers are not smart and nod off at the wheel, the futuristic vehicles they will be driving will find their way home the way a family horse did in olden days. As Robert Frost's little horse of yesteryear thought it queer to be stopping by woods on a snowy evening, wondering if there were some mistake and giving its harness bells a shake in inquiry, so the automobile of tomorrow promises to question and warn us and even take control of matters when we try to do something foolish, like approach at full speed a car stopped ahead; move into a passing lane when another vehicle is on our flank but not visible in the side-view mirror; drift across the lane or edge markings on the pavement; or drive past our exit.

Such driving aids are already available today, and the vehicle equipped with them communicates with the driver through a combination of aural, visual, and haptic prompts. Drivers become conditioned to and react to different numbers and tones of beeps, blinking and flashing lights and icons, or vibrating steering wheels and seats after a surprisingly short period of acclimation. Some of the systems are so sophisticated that they act when the driver does not, steering the car back into its lane or stopping the car automatically in an emergency. Some cars can park themselves, and a four-wheel-drive Tesla equipped with an autopilot will perform automatic lane changing when the driver signals his intention to do so. And, of course, in just about any car now, when we miss a turn the GPS navigator we are using will inform us that it is recalculating our route or that we should make a legal U-turn as soon as conditions allow.

Vehicles also are equipped with devices that can check the pressure in all four tires simultaneously and display on the now-ubiquitous center screen the results along with the correct inflation pressures. Sophisticated cruise control systems can not only maintain a steady speed but also can maintain a fixed number of safe car lengths between our vehicle and the one in front of us. This kind of smart control is achieved with such smoothness of deceleration that the driver having set the cruising speed at 65 miles per hour will realize that his speed has been reduced to 55 only when every other car on the highway is passing both him and the slowpoke in front of him.

Adjust Speed

Even on the darkest evening of the year, the headlights of today's cars brilliantly illuminate the dark and deep woods beside the road, some dimming themselves as traffic coming in the opposite direction warrants. When we wish to pull off the highway and onto a dirt road leading up to a farmhouse, the headlight beams will shift from pointing straight ahead to pointing left or right, depending on which way we are turning. Smart windshield wipers know to start working when a few drops of water strike the glass, and they adjust the speed of their sweep according to how heavily it is raining.

Experiencing such features in the cars of today, we

URGE APPROPRIATION FOR GOOD ROADS.

WASHINGTON, D. C., Jan. 25.—President W. H. Moore, Secretary R. W. Richardson and other officers and committeemen of the National Good Roads association, gathered in Washington today for the purpose of carrying the good roads campaign into congress. The members will appear before the appropriations and other committees of congress and present the resolutions of the last convention of the National Good Roads association, urging appropriations for improvement of public highways throughout the United States. The association, it is said, will not indorse any particular bill, but will confine its efforts to making a strong argument for good roads legislation. The Brownlow bill, introduced by Representative Brownlow of Tennessee, providing for federal aid in road building, is now pending in the house.

A 1904 newspaper cartoon by E.A. Bushnell endorsed the National Good Roads Association, which was affiliated with the Good Roads Movement.

might wonder what the future will bring. Will windshield wipers detect and clean off tree sap that streaks the glass? Will underinflated tires fill themselves even as we travel down the interstate? Will the illumination of the low-fuel warning icon trigger the GPS to identify the nearest gas station selling our preferred brand of fuel at the lowest local price and automatically direct us there? And if the distance to the pump is greater than the estimated miles of fuel left in the tank, will the car be slowed to the appropriate fuel-efficient speed to get us there before we run out of gas? These are the kinds of questions inventors and engineers pose to themselves on the way to improving present-day technology to make it future technology.

The aftermath of the 2013 Skagit River Bridge collapse in Washington. It had been classified as fracture-critical.

But the features just described have to do more with vehicles than with the roads and bridges upon which they rely. Already it is commonplace to have detectors embedded in the pavement at intersections to tell traffic lights whether there is a vehicle waiting to make a left turn. If there is not, the left-turn arrow does not appear and traffic coming the other way is given the green light without delay. There are also smart open roads and bridges, pieces of smart infrastructure that in essence monitor themselves and alert engineers and others when they are in need of attention. A roadway can be embedded with sensors that detect snow and ice conditions, signaling when road crews should be dispatched. Bridges can be fitted not only with sensors but also with devices controlled by the sensors. Thus, when ice begins to develop on a bridge surface, the sensors that detect it can also trigger a system embedded in the curb or guardrail that sprays anti-icing solution over the pavement without human intervention.

Another use of such technology is to fit a bridge with devices that can detect when a beam or girder in the structure has developed a serious crack or corrosion. It is expensive to wire a large number of such devices to a data-collection computer that can communicate with, say, the state department of transportation, but if the devices are wireless, the installation can be done much more easily and efficiently. One heavily used piece of infrastructure that would have benefited from detection devices is the Interstate 495 bridge over the Christina River in Wilmington, Delaware. In mid-2014, human inspectors found that a number of the piers supporting the approach viaduct were out of plumb and that the structure was leaning. The section of highway was closed while the problem was evaluated and, eventually, corrected. The viaduct, which ran over largely vacant industrial land, had been damaged when a 50,000-ton pile of dirt was illegally placed atop an area beside the bridge piers, causing the ground to shift and so damage the piers. Had they been fitted with sensitive wireless tilt meters akin to the kind that tell a smartphone or tablet which way is up, data indicating the abnormal condition might have been collected by a computer and sensor-filled truck on a routine pass over the bridge. Earlier detection of the problem would likely have arrested the progressive damage and gotten the bridge back in service more quickly and at less expense.

Functionally Obsolete

In another case, in 2013, a bridge carrying Interstate 5 over the Skagit River in Washington State collapsed and fell into the water after an oversize truck hit parts of the overhead steel structure while passing through one of its truss spans. The 58-year-old bridge had been considered functionally obsolete, forcing traffic in the right-hand lane to drive very close to the side of the structure, where the overhead braces curved downward and so reduced vertical clearance. There had been a history of tall vehicles striking these structural parts, but the bridge had survived prior impacts. In addition to this problem, the Skagit River Bridge was also classified as fracture-critical, making it like the interstate bridge in Minneapolis that had collapsed six years earlier, claiming thirteen lives. No one died in the Skagit River Bridge collapse, but that was only a matter of luck.

Outfitting a bridge like the one over the Skagit River with sensors that detect a too-high oncoming vehicle would be easy to do. We already are familiar with devices that measure a vehicle's speed by radar and display it on a sign beside the highway, thereby providing a warning to the driver to slow down. The augmented cruise control systems that keep a car a safe distance from the one in front of it use lasers and a computer to maintain a specified separation. Imagine a smart bridge with low clearance fitted with a similar device that could also communicate with an approaching tall but smart truck and slow it down to a stop before it impacted the bridge. That kind of wireless connection between bridge structure and vehicle could obviously prevent collapses and deaths. In time, it is likely to be a common reality.

Engineers are currently working on highway-vehicle systems that maintain a constant wireless connection among vehicles within a few hundred yards of each other traveling along the same stretch of highway. In such a system, two cars not visible to each other—either because there is congested traffic between them or the one ahead is rounding a blind curve—would be able to maintain contact. If the leading car has to stop suddenly, it would send a signal to the following car to apply its brakes also—and do it automatically.

Connected-Vehicle

Other so-called connected-vehicle technology could lead to the elimination of stop, yield, and other traffic signs. If all vehicles in the vicinity of an upcoming intersection were part of the wireless network, the computer in a car approaching the intersection could know whether there would be cross traffic. If so, the driver would be alerted to approach with caution or stop, and perhaps even have a bright electronic stop sign displayed on a navigation screen, if not as a hologram directly in the driver's line of sight. If the intersection is anticipated to be clear, no warning would appear and the car would not even have to slow down. If all vehicles were part of such a system, traffic signs and lights could be eliminated entirely, thereby unburdening a transportation department of the need to purchase, install, and maintain such things. Furthermore, a highway without physical signs would be a less visually cluttered and hence a less distracting and more attractive and environmentally friendly road.

In the summer of 2014, the U.S. Department of Transportation announced its plan to require in the not-too-distant future the installation of vehicle-to-vehicle communication technology in all cars and trucks, new and old. Fitting a vehicle with a transmitter is projected to add about $350 to the cost of a new car in 2020; an existing car could be retrofitted with an equivalent device. Engineering research teams connected with universities, government laboratories, and the automotive industry are already testing the technology. As part of a program at the Michigan Transportation Research Institute in Ann Arbor, volunteers are driving almost three thousand transmitter-equipped vehicles in actual traffic conditions.

Completely driverless cars are already a reality, though so far only as prototype vehicles. The development of such vehicles has been promoted for years by the U.S. Department of Defense, which through its Defense Advanced Research Projects Agency has for some years been sponsoring driverless-car challenges, offering prizes as high as $2 million for unmanned vehicles successfully negotiating urban and battlefield courses. Building on the successes of such programs, Google has been working on the development of driverless automobiles since 2009, and in the subsequent five years such vehicles drove themselves autonomously for more than seven hundred thousand miles on public roads. The automotive industry has also been actively developing its own autonomous technology. An Audi Q5 outfitted with a computer system processing data from onboard instruments including cameras, radar, and laser sensors in early 2015 completed a 3,400-mile trip from San Francisco to New York City, during which it behaved as an autonomous vehicle and steered itself 99% of the time. It was only in very complicated traffic situations like construction zones that a human driver had to take over the wheel. Tesla Motors introduced its Model S electric-powered sedan in 2012 and added a self-steering feature called Autopilot in 2014. Elon Musk, chief executive officer of Tesla, promised a fully autonomous vehicle by about 2020. General Motors was expected to introduce in 2017 technology in its Cadillac that will allow no-hands highway driving. The configuration of cars will naturally evolve with the use of such technology, and in time we can expect front seats to swivel around so that, if they wish, everyone in the vehicle can play card and board games, converse face-to-face, or catch up on email, send text messages, and otherwise immerse themselves in antisocial media.

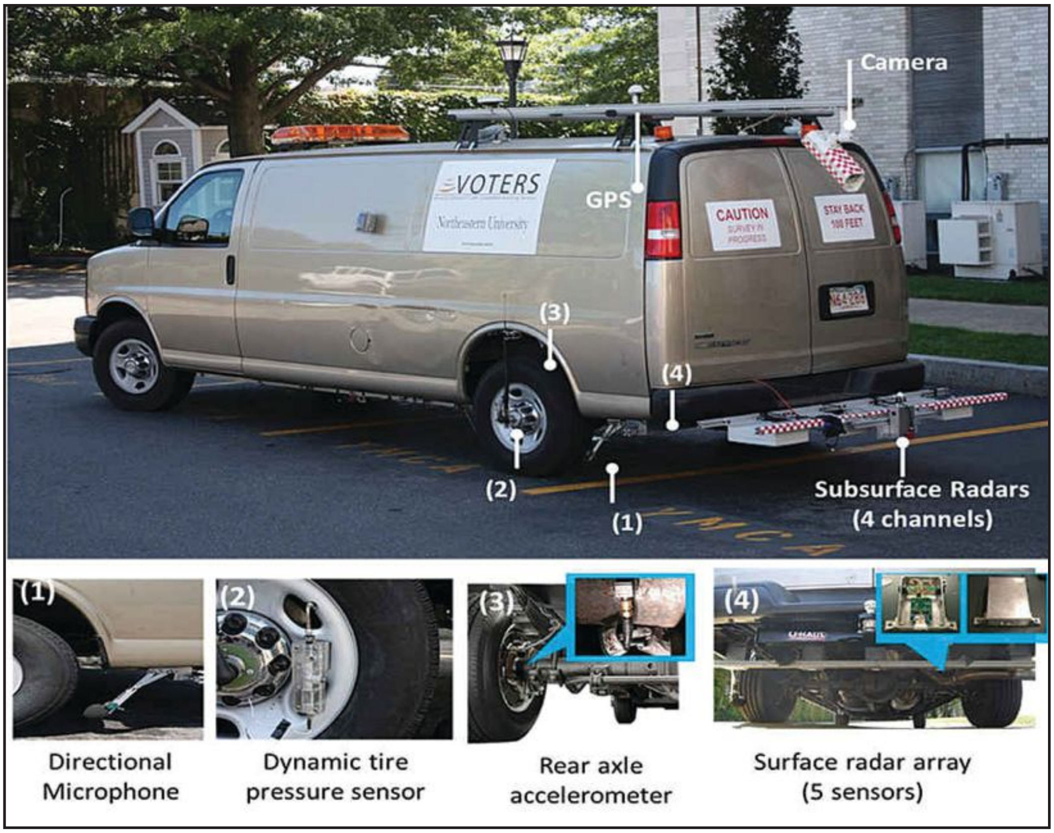
But the road to the future is seldom without potholes or speed bumps. The whole concept of autonomous vehicles was dealt a serious setback in May 2016 when a Tesla Model S being driven with its Autopilot feature engaged did not detect a tractor trailer making a turn in front of it and slammed into the side of the truck at full speed. At first, the fatal accident was blamed on human error, since the driver seems not to have been watching the road or heeding warnings that he be prepared to take over control of the car at any moment. In the final analysis, the National Transportation Safety Board, which investigates airplane crashes, bridge collapses, and the like, placed at least some blame on the automaker itself for allowing its system to be misused the way it was.

"Data Donors"

Even when a vehicle's occupants do not have their eyes on the road, they can help inspect and maintain it by being "data donors." This is a concept introduced by New Urban Mechanics, a group dedicated to "an approach to civic innovation focused on delivering transformative city services to residents." In 2010, the Mayor's Office of New Urban Mechanics was formed in Boston, later joined by an analogous city agency in Philadelphia, each serving as an "innovation incubator" by "building partnerships between internal agencies and outside entrepreneurs to pilot projects that address resident needs."

Specific projects ranged from improved trash cans to high-tech smartphone apps. Among the apps is Smart-Bump, which tracks an automobile's ride over Boston streets. After the free app has been activated, the smartphone can be placed on a car's dashboard to monitor the ride. The accelerometer in the phone detects bumps, and

This graphic shows the VOTERS system devised at Northeastern University to survey road condition. *Image courtesy of Environmental Systems Research Institute, Inc. (Esri).*



software distinguishes a bump due to hitting a pothole from one due to riding over a manhole or a speed bump. Where the vehicle does go over a pothole, the detected movement is paired via GPS with the location, and the data are sent— this is the data donation—to the appropriate city department that monitors the condition of the streets. When a pothole is identified, a road crew is sent to fill it.

Engineers at Northeastern University have taken the concept a bit further with their Versatile Onboard Traffic Embedded Roaming Sensors, a mouthful no doubt forced to yield the acronym VOTERS. Vehicles driving a lot of city streets each day are outfitted with a variety of sensors that measure such things as tire sound, pavement surface defects, and subsurface delamination—data that when properly interpreted provide information on precursors to potholes. Suspect conditions can be monitored and repairs done when there are signs of a pothole beginning to form.

Thing of the Past

Potholes themselves may be a thing of the past if researchers succeed in developing self-healing asphalt. One of the most prominent of these researchers is Erik Schlangen, a professor of civil engineering at Delft University of Technology in the Netherlands and leader of a group doing research in experimental micromechanics. By adding short steel wool fibers into a mix of asphalt concrete, cracks that develop in the pavement material can be healed when it is subjected to microwaves. Schlangen has demonstrated the process in a six-and-one-half-minute TED talk, in which he breaks a small beam made of asphalt in two, places the two halves together in a microwave oven, and by the end of his talk removes a rejoined bar. His hope is to develop an industrial-scale microwave device that can be transported in a highway vehicle and perform the same kind of healing by induction.

Self-healing concrete pavement made from Portland cement is also on the horizon. It can be made by incorporating into the concrete mix tiny capsules containing dormant bacteria capable of producing limestone when activated. This will happen when the concrete develops a crack that causes the encapsulated bacteria to be released and that allows water to reach the bacteria, thus enlivening them to do their work. Once activated, the bacteria consume a starchy substance that was incorporated into the concrete mix and excrete calcium carbonate, which is essentially limestone, thus plugging the crack and forestalling further damage. Structures formed of such concrete have recovered as much as 90% of their uncracked strength.

The roads of the future promise to be smooth and quiet, as will be the ride in all-electric vehicles that occupants will no doubt take for granted. The experience, however, may not be quite the same as Norman Bel Geddes laid out in the General Motors Futurama exhibit and in his book, *Magic Motorways*. It is likely to be far superior.

Whether our roads and bridges can actually evolve to such an idyllic state in the foreseeable future will depend upon how well we care for them in the interim.

If America's highway infrastructure is allowed to deteriorate much below its current state, the cost of just maintaining it in a condition no worse than it is now could be overwhelming. Almost every dollar budgeted for roads and bridges, whether at the federal, state, or local level, will have to be earmarked for repair and replacement work just to restore the status quo ante rather than advance the technology and apply it broadly.

Government-sponsored research and development of smart materials and systems will have to take a backseat to filling potholes, resurfacing roads, and rebuilding broken bridges. And the longer we wait to do those things, the more there will be to fill, resurface, and rebuild, which will, of course, take even more money.

Since first issued in the late 1990s, the infrastructure report cards, now updated every four years by the American Society of Civil Engineers, have publicized the dire state of affairs. Ironically, the category of bridges, which have become symbols for the assortment of public works collectively termed "infrastructure," has received among the highest grades. But a gentleman's C, defined by ASCE itself as "mediocre," should not be the nation's goal. It should signal plenty of room for improvement, not only in aspirations toward better-quality materials and workmanship but also toward more durable structures and systems.

Neither voters nor elected officials should be satisfied with or tolerate the mediocre to poor infrastructure that we are told our nation now possesses. In fact, we should be embarrassed. We as a nation should want our public works to be better than they are.

The country has pulled itself out of infrastructural ditches before. The Good Roads Movement begun by cyclists in the late 19th century led to improved roads that were enjoyed by recreational cyclists and early motorists alike. The firsthand experience of Lt. Col. Dwight Eisenhower in an army convoy and of other pioneers who embarked on transcontinental journeys in early motor vehicles brought to the fore the need for national roads. In the 1920s, the plight of farmers struggling to get their wares to market over unimproved rural roads attracted the attention of champions in Washington, who pulled the farmers out of the mud and onto an improved system of farm-to-market roads. And in the 1930s, even as federal road-building projects were providing jobs during the Depression, plans were advancing for a network of interregional highways that in the latter 1950s began to be realized in the interstate highway system. But by 2006, the year the fiftieth anniversary of the landmark interstate legislation was celebrated, there was a general recognition that the interstates themselves were growing old and in some places had become inadequate to their task.

Stimulus Package

The American Recovery and Reinvestment Act of 2009, touted as a stimulus package for the economy, was very visibly credited on large signs announcing highway improvement projects it funded, but the total amount of money devoted to them was barely 4% of the bill's approximately $800 billion total. We are still in an infrastructural ditch.

According to the American Society of Civil Engineers report card for 2013, the average age of America's bridges was forty-two years, and more than 30% of the spans were beyond their fifty-year design life. In times of tight budgets, there is necessarily a tension between the increasing cost of maintaining aging bridges in service and replacing perhaps even younger ones that are structurally deficient. Collectively, the latter group includes about 10% of all bridges in the United States, and these carry approximately a quarter of a billion vehicles daily.

Occasionally such a bridge will collapse without warning, as the one carrying Interstate 35W across the Mississippi River in Minneapolis did during an evening rush hour in 2007. It is to preclude such tragic accidents that conscientious surveillance, maintenance, and replacement of bridges and other existing infrastructure is obviously so important.

Properly maintaining and, when and where needed, upgrading and expanding our infrastructure, not only ensures that we have safe roads and bridges but also contributes positively to our quality of life, to our outlook for the future, and to the national economy. Shortchanging our investment in the infrastructure is shortchanging the well-being and optimism of future generations and the prospect for economic growth. Especially during slow economic times, allocating resources for infrastructure projects can provide not only much-needed jobs for the unemployed but also conspicuous productive activity at construction sites, thus promoting an ethic of work and progress even in the leanest of times.

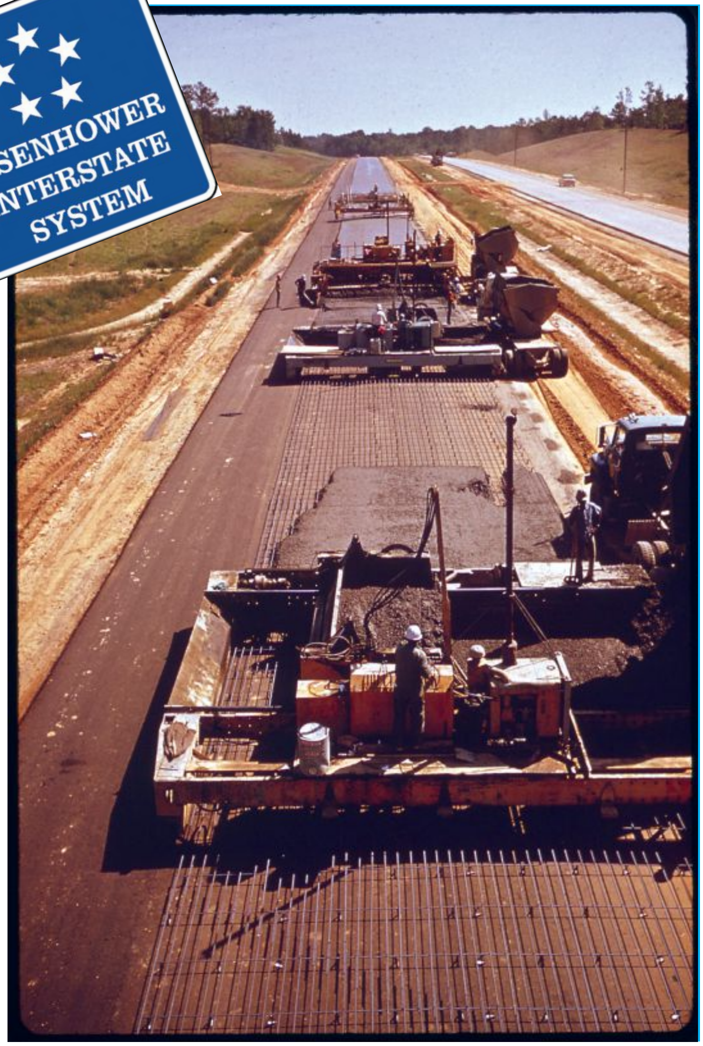
We citizens can do our part to promote safe and robust infrastructure by actively and enthusiastically encouraging and supporting legislation that provides appropriate funding for infrastructure needs, replenished as needed through adequate and reliable sources of revenue. These generally will take the form of taxes and fees, which when fairly levied should be responsibly paid. For roads and bridges, as in all infrastructure categories, we should look to making the means of funding stable and predictable, so that state highway departments need not engage in triage that forces them to choose between whether to replace a structurally deficient bridge that is beyond its design life or to build a new and wider bridge to carry more traffic through a congested area.

No one likes to pay taxes, but they obviously are necessary to give us the roads and bridges and other forms of infrastructure that we have come to expect and appreciate. But expecting to drive over smooth pavements and adequately wide bridges should not be seen as a luxury that we can casually forgo in tough times. Poor roads and bridges actually cost households and businesses money in terms of increased commuting time, additional fuel use, and larger vehicle maintenance bills, in addition to higher prices for consumer goods whose distribution costs are higher.

According to the ASCE Failure to Act estimate, the nation's degrading infrastructure could cost American households over the period from 2012 to 2040 in excess of $150 trillion, not accounting for inflation. That alone should be reason enough to support investment in infrastructure.

Broader Implications

I was certainly not aware of such dilemmas when I was a young child playing on the edge of Brooklyn infrastructure in the aftermath of a thunderstorm. Squatting on the curb between sidewalk and street, my only focus was on the storm water flowing swiftly in the gutter. There was no need for me to think of the broader implications of where the water went after it passed by me and spilled into the sewer. Nor was there any need for me to know anything about the granite curbstone that separated the concrete sidewalk and asphalt pavement. As long as it supported me in my play, I was happy. It did not matter to me then that the street on which I played ran down to the Gowanus Canal, about a mile away. As children we measured distance in city blocks, and a mile was too far for a four-year-old urbanite to contemplate. Since the Brooklyn Bridge was about two miles away from my



Steel rods, made from shredded autos, being used for reinforcement in this section of I-55, north of Durant, MS, in 1972. It takes 2,200 autos to make one 2-lane mile of steel reinforcement.

house, it might as well have been on a different planet. It did not capture my imagination then that older children and adults on foot or wheels could navigate along the streets and avenues and through the subway tunnels in the vicinity of my house all the way through downtown Brooklyn and on into Lower Manhattan, even though I knew that my father did it every workday.

By the time I was a teenager and drove my father's car past the construction sites of the Verrazano-Narrows and Throgs Neck bridges, I did begin to understand the interrelatedness of infrastructure. I understood that these bridges could not be built without consideration of the roads that brought traffic to them and carried it away from them. Infrastructure was like skeletal anatomy: the street is connected to the avenue; the avenue to the boulevard; the boulevard to the bridge; the bridge to the highway; and the highway to the world beyond. I also began to understand that these pieces of infrastructure did not last forever. Even the granite curb would wear down with use.

Growing up and stepping back from the curb provides a broader perspective. Reflecting on their history, it is easier to understand where roads come from and where they lead to, how they got their lines both white and yellow, how traffic on them was tamed with signs and lights, and why today's roads so often trace the same path as bison did in early America. The story of infrastructure, even in its smallest details, is one of growth and change in response to problems, but it is also one of expansion of systems and repetition of process.

The problems of the past remain the problems of today, only embedded in different technology, complexity, and bureaucracy. Just as a poem written a century ago about making choices can remain relevant today, so do the stories of the design, planning, and construction of roads and bridges from earlier times. Whatever roads have been taken or not taken to get us to the present state of our infrastructure, the lessons of the past can help us better comprehend how we can put it back in order.

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