BIG DIG, BIG BRIDGE

Henry Petroski

Last March I traveled to Boston to give a talk to a student meeting hosted by the Boston Society of Civil Engineers Section (BSCES) of the American Society of Civil Engineers (ASCE). The cumbersome name of the local organization stems from the fact that the Boston society, the oldest permanent engineering society in America, wanted to retain its identity when in 1974 it became a section of the ASCE, the oldest *national* engineering society. The distinction was clear at the meeting, where an ASCE banner hung from the front of the lectern, while a much larger BSCES banner hung higher on the wall behind it. The former bore the date 1852, that of the founding of ASCE; the latter bore the date 1848, that of the founding of BSCE.

Boston is a proud and historic city, and it boasts well-established traditions in education and politics, in the arts and sciences, and in engineering and construction, the latter of which literally shaped the city. The development of the prestigious Back Bay area dates from 1814, and the oldest structures on Beacon Street date from 1828, when they were built along the mill dam that separated upper and lower basins and provided a head of water to power mills. Almost 500 acres of land were created through the use of fill in the middle of the 19th century, and this land constitutes today some of the most valuable property in Boston.

Growth Pains

A century later, engineering and construction left a quite different mark on the city. By the 1940s, it was evident to transportation planners that automobile traffic would soon overwhelm downtown streets if something were not done. An elevated highway, with on and off ramps convenient to the many neighborhoods along the way, was believed to be the answer. The Central Artery for local traffic was to be supplemented by the Inner Belt, which would have allowed through traffic to bypass downtown by using a highway going through, among other areas, Back Bay. A master plan to effect such transportation routes was formalized in 1948, and construction on the Central Artery began in 1950.

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The first phase of construction began north of downtown, in Charlestown, and proceeded across the Charles River and south. In 1954, the first section of the Central Artery, along with the Sumner Tunnel to East Boston (and the airport), was opened to traffic—and to terrible reviews. The elevated highway was ugly to look at, unappealing to walk under and confusing to drive over. The continuation of the highway southward was constructed underground. By the end of the decade, the Central Artery was carrying 75,000 vehicles daily, including the through traffic that was to have been diverted to the Inner Belt. But the Inner Belt was never built, because residents along its route, seeing what effect the elevated highway had on neighborhoods surrounding downtown, successfully protested against it. As the end of the century approached, almost 200,000 vehicles per day were using the Central Artery, and traffic jams were daily occurrences, often preventing frustrated travelers from reaching the airport on time.

To rectify the situation, planning for the Central Artery/Tunnel Project, now commonly known as the Big Dig, began in 1982. Funding was approved in 1987, and construction began in 1991. (There was, of course, a lot of political wrangling in between.) In principle, the concept was simple: Move the elevated highway underground. In fact, the challenge was virtually without precedent: Construct tunnels beneath an elevated highway without disturbing the highway itself or interrupting the traffic it carried—or the subways or activity in the nearby buildings or the maze of water pipes, sewer lines, utility conduits and other infrastructure that underlie any large city. In addition, noise and other annoyances that go along with heavy construction were to be kept to a minimum. The projected cost was \$4 billion, in 2003 dollars; the actual cost at the end of 2003 was almost \$15 billion. As quoted on the Big Dig's Web site, it is "the largest, most complex and technologically challenging highway project in American history."

La Diaframma

The success of the project rested literally and figuratively on the mushy-sounding technology of "slurry walls." The slurry-wall technique originated in Italy and was brought to America in the

1960s, when George Tamaro, then an engineer on the staff of the Port of New York Authority, was sent to Rome to learn about reinforced-concrete design as practiced by Pier Luigi Nervi. Nervi, whom Princeton engineering professor David Billington has described as a "structural artist," introduced Tamaro to the foundation technology known in Italian as *la diaframma*. A concrete diaphragm or slurry wall essentially provides a waterproof barrier around a construction site, and the wall can be constructed to great depth without disturbing nearby structures. It was the perfect technology to employ in building the foundations of the Port Authority's World Trade Center, which had to be designed in such a way that the waters of the Hudson River—and the earth pressures associated with surrounding buildings—were kept at bay.

A slurry wall is begun by digging a deep, relatively narrow ditch, whose unsupported sides would normally be expected to collapse inward during construction. They are kept from doing so by replacing the excavated dirt with a slurry—a thick mixture of water and clay—that supports the sides of the ditch. When the excavation reaches the bottom of the ditch, which is usually located at bedrock level, a cage of reinforcing steel is lowered into the slurry and concrete is introduced into the ditch. This in turn displaces the slurry, which can then be pumped into storage vessels for further use in a newly dug part of the ditch. When the concrete cures, a waterproof slurry wall resting on bedrock is in place.

In Boston, about five miles of three-foot-thick slurry wall were built. It was made strong enough to support temporary structures onto which the weight of the elevated highway (and its traffic) could be transferred. Once that was accomplished, the old highway supports could be removed and tunnel excavation begun underneath. Most of this was done while street traffic continued, supported by steel beams and concrete decking spanning the slurry walls. In all, over 500,000 truckloads of dirt were moved. As the space between slurry walls was cleared, they had to be shored up to prevent any inward movement. Not only did they support the elevated highway above, but they also had to prevent any lateral ground motion adjacent to nearby buildings. The slurry walls, which served so many purposes, were also designed to serve as the permanent sides of the completed tunnels.

In addition to the construction of tunnels beneath the elevated highway, the Big Dig involved making on and off access ramps and new tunnels across the harbor and other waterways. These tunnels did not employ slurry walls but were constructed by other means. Among the structures is the Ted Williams Tunnel, which connects the Central Artery with Logan Airport. Getting to the Boston airport was long an anxiety-ridden task. I recall many times being caught in gridlock traffic that inched toward the old Callahan Tunnel. One of the few times I missed making a flight owing to traffic was in Boston.

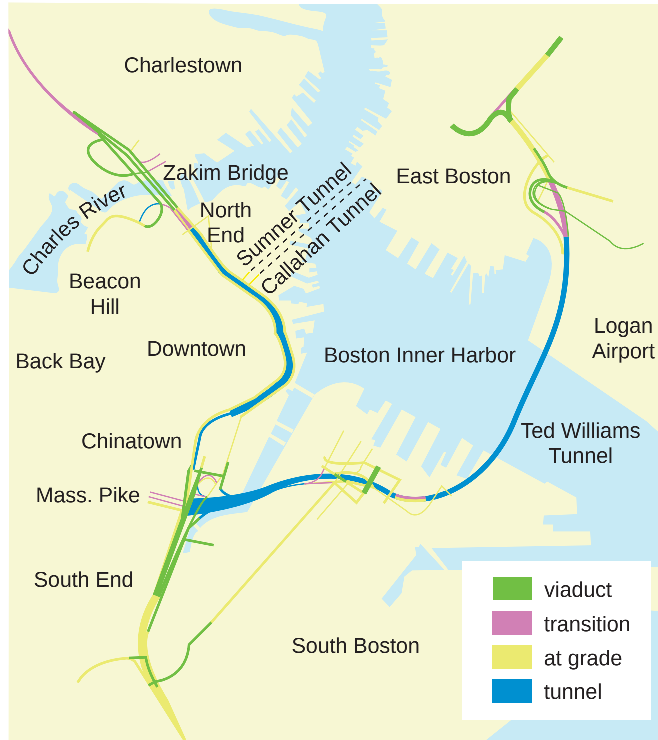

Figure 1. Boston's Big Dig has been touted as "the largest, most complex and technologically challenging highway project in American history." It has entailed moving much of the Central Artery underground and building a new harbor tunnel and two new Charles River bridges. (Map adapted from the Central Artery/Tunnel Project.)

The Ted Williams Tunnel was among the first parts of the Big Dig on which construction commenced. It began with what have been described as binocular shaped tubes fabricated in a Baltimore shipyard. With their ends sealed, 300-foot-long sections of these buoyant tubes were towed to Boston, where they were outfitted with concrete roadways and other necessities. In the meantime, trenches were dredged in the bottom of the harbor. The tubes were finally towed out over their final resting place and sunk into it. The sunken tubes were welded together end-to-end, and, when they were watertight, the end seals were removed. The Ted Williams Tunnel was the first part of the Big Dig project to be completed; it opened to traffic in 1995. Other parts of the Central Artery / Tunnel Project were opened to traffic at various times during 2003.

The Big Dig's Big Bridge

Prior to leaving for the civil engineering society meeting, I was in contact with a former student of mine who now works in the Boston area. He was kind enough to offer to pick me up at my hotel and drive me around the newly opened Big Dig, as it is still called and will likely be called even after the last vestiges of excavated dirt are removed, the old elevated highway known variously as the "green snake" and the "green monster" (after the sickly colored paint job that was

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Figure 2. Leonard P. Zakim Bunker Hill Bridge is arguably the most successful aspect of the Central Artery/Tunnel Project, aesthetically and economically.

visible where there was no rust) is trucked away, and the last pieces of yellow construction equipment disappear.

My travel to Boston had been complicated by the cancellation due to mechanical problems of my direct flight, requiring me to change my itinerary and catch a connecting flight in Washington, D.C. Cancellation of the flight to Washington was also threatened by a mechanical problem with the nose gear, and I watched with great interest as a maintenance crew changed the two front tires on the regional jet. They finished just in time for the plane to take off, reach Washington and allow me to make my connection. I arrived in Boston in the late afternoon and went directly to my hotel, which was at the airport so I would not have to worry about traffic when getting to my early flight the next morning. On checking in, I asked for a room with a view and was pleased to find my room facing west across the harbor and toward the Boston skyline. The sun was low on the horizon, making it difficult to see much detail, but to the north of downtown I could make out the two pylons of the city's new signature bridge, which is the most visible and perhaps the most talked-about part of the Big Dig. (The numerous large ventilation buildings, so necessary to remove carbon monoxide from vehicular tunnels, generally go unnoticed, unless one looks to their roofs and recognizes the cleverly disguised exhaust stacks that emanate from them.)

Bostonians already have come to refer to the awkwardly named Leonard P. Zakim Bunker Hill Bridge by its shortened name, the Zakim Bridge. Nonetheless, both parts of the full name are appropriate. The bridge is situated in the shadow of Bunker Hill and the obelisk-like monument that commemorates the Revolutionary War battle. Indeed, the tops of the bridge's inverted-Y-shaped pylons echo the shape of the monument. In addition, being part of the project that symbolizes correcting past wrongs and restoring dignity to neighborhoods slashed by the Central Artery, the bridge across the Charles also memorializes Leonard Zakim, a civil-rights activist who for 20 years served as regional executive director of the Anti-Defamation League.

The Zakim Bridge is generally considered the most successful component of the Big Dig. Ironically, this aboveground symbol of what burrows beneath is looked on most favorably. At a cost of around $100 million, the bridge is considered a bargain compared to the overall project cost. (A significant portion of the inflation of the total project cost is attributed to expenditures related to mitigating the noise, dust and annoyances of construction generally; this precedent is expected to be one of the more enduring legacies of the way the Big Dig was managed.)

The story of the design and construction of the Zakim Bunker Hill Bridge is as involved as its name. A new structure and interchange were necessary to carry the north-south highways I-93 and U.S. 1 across the Charles River, and many alternatives, ranging from bridges to tunnels, were explored. The first 26 schemes were designated A through Z, and Frederick Salvucci—the neighborhood activist who became state secretary of transportation and in that position the visionary who pushed the Big Dig through political minefields—was in favor of Scheme Z, which included a major bridge structure. Salvucci sought approval for it just before the end of the term of Governor Michael Dukakis, who after losing his presidential bid decided not to seek reelection. On the very last day of the Dukakis administration, hotly contested environmental permits were approved, but with a strong recommendation that Scheme Z be reconsidered.

The complexity of the interchange had been ridiculed as being a "spaghetti bowl" of intertwined roads and ramps and loops that required some vehicles to cross and recross the river to reach their destination. (The term "spaghetti bowl" was also used to describe the mess of utility lines and cables that lay under the streets beneath which the Big Dig tunnels were to be dug.) A tunnel under the Charles was looked at anew, but environmental issues relating to disturbing the polluted riverbed and the high cost clearly favored a bridge. Unfortunately, carrying out Scheme Z required an abnormally wide bridge that environmentalists opposed for the heavy, dark shadow it would cast on the river and architects opposed because they did not see how such a bridge could be made attractive.

Engineers have been accused of saying, "If you can't fix it, feature it." One way to remove objections to the width of the bridge was to engage a world-class bridge designer whose reputation for beautiful, distinctive bridges was beyond question. The engineer engaged was the Swiss Christian Menn, considered to be the premier bridge designer in the world. Menn's design for Boston was brilliant, turning liabilities into features and doing so within the constraints of the existing Central Artery. Among its distinctions, the Zakim Bridge is at 10 lanes the widest in the world, and with two of its lanes cantilevered outside the pylons, it is the only asymmetrical cable-stayed bridge in the United States. These features are noted with pride by Bostonians when describing their new signature bridge.

Reunion and a Tour

Soon it was time to stop musing about the bridge and leave the hotel room to go meet my ride. It was good to see my former student after so many years, and we quickly caught up on family and travels. Our conversation soon changed to the Big Dig as we approached the tollbooths at the entrance to the Ted Williams Tunnel. Paying the toll marked the last time we stopped for quite a while. Even though it was the beginning of rush hour, traffic moved freely and seamlessly from the airport onto I-90 West, which becomes the Massachusetts Turnpike just the other side of the interchange with I-93. We did not go as far as the Mass Pike, however, but merged easily onto I-93 north and were soon traveling under the downtown streets in one of the newly opened central artery tunnels (which will be closed during the Democratic National Convention in late July).

My impression of the tunnels was divided. The Ted Williams Tunnel appeared bright and clean and new. It cannot but make a very positive impression on first-time visitors to the city as they ride in from the airport. I cannot say the same about the I-93 central artery tunnel. Even though

Steven Senne / AP

Figure 3. I-93 central artery tunnel *(shown here prior to opening)* is to the author's eye less pleasing than the new Ted Williams Tunnel beneath Boston's Inner Harbor.

opened to traffic only a few months before my visit, the tunnel looked dirty and old. The wall tiles, which stop short of the ceiling (a "value engineering" decision that saved less than one-half of one percent of the total project cost), seemed darkened with soot and grime. If this was the dust and soil of construction left unremoved before opening, one can only wonder why. Exposed cables hang from the walls above the tiles and present the appearance of being added as an afterthought, as if the tunnel were designed without any consideration of integrating utilities in a more aesthetically harmonious way. It reminded me of a tunnel built before electricity or fiber optics that had been retrofitted with the newer technology. Rather than being subtly integrated into the design, ubiquitous ventilation grates and louvers are conspicuous in the tunnel, as if to remind travelers that there is plenty of fresh air in the confined space through which they are driving.

My aesthetic disappointment with the central artery tunnel did not end with the tiles, cables and grates. Where I would have expected straight lines or gentle transition curves in the alignment of lights, there appeared to be abrupt transitions—as if two work crews had met with their levels and lines a little off and did not know how to correct the errors. This kind of distracting finishing to bridges and tunnels can leave a poor impression on observers who are not fully aware of the difficulties of working out the last small details on an enormously large project.

Among the final and most important details on any highway project is the signage. The traffic signs in the tunnel look like standard white-on-green interstate issue, as they should be, but the mounting of the hardware seems a bit awkward. Obviously, direction and exit signs cannot be supported by poles planted in a median (opposing traffic travels through separate tunnels) or in grass beside the shoulder. Instead, the overhead signs are suspended from the ceiling—leaving little if any space between sign and ceiling—creating an oppressive feeling of drastically reduced headroom.

Zakim Bridge Up Close

The Big Dig tunnels amount cumulatively to about 160 lane miles, but when that number is divided by 2 to account for both directions of the highways, and that result is divided by 3 or 4 to account for multiple lanes each way, and when underground connectors, ramps, and entrance and exit lanes are taken into account, the total distance a driver remains underground is not very great. (Only about a third of the entire Big Dig project is underground.) In my guided tour, light soon appeared at the end of the tunnel, and as we emerged from it we quickly found ourselves on the Zakim Bridge, crossing the river and heading into Charlestown.

The bridge that I had admired from across the harbor was not in the least disappointing close up. As with most cable-stayed bridges, its cables provide wonderful plays of light and shadow across the roadway, and the ever-changing patterns and perspective in which they envelop in a diaphanous tent drivers and passengers traversing the main span makes for a delightful experience. The rhythmic morphing of lines and planes makes music of geometry—the driving equivalent of enjoying the sounds of a harp concert. The only disappointment in crossing the Zakim Bridge is that its modest span makes the experience too fleeting. Overall, the bridge is only 1,432 feet long, and its main span is just about half of that—745 feet supported from the twin 270-foot-tall towers by a tent of cables. (By comparison, its width is 183 feet, which highlights the design challenge of making the bridge appear as well-proportioned as it does.) The side spans, which make up the difference in length, are each supported in the center by only a single plane of cables, an arrangement made necessary by the confined area in which the bridge was built while traffic continued on the old Central Artery.

Stories about Boston's new signature bridge abound. One of the most frequently repeated by engineers is that of Christian Menn's concern during a site visit when he saw steel reinforcing bars being installed so close to one another that he believed that there would not be sufficient space to allow concrete to flow readily into all the interstices. Voids in the concrete did in fact result, and repairs had to be made before the bridge even opened. Such problems are generally considered minor by American contractors, but for artists like Menn, whose bridges not only bear traffic but also serve as pieces of sculpture that enhance the landscape and uplift the spirit, they are aesthetic and technical blemishes.

In any case, driving in traffic over the Zakim Bridge simply does not allow enough time to appreciate all the graceful aspects of the structure. Fortunately, our plan was to continue on I-93 north only a short distance into Charlestown before turning around and heading back on I-93 south to approach the bridge from a different angle and cross it again. (Another way to view the bridge is from the more or less parallel Storrow Drive Connector Bridge—also part of the Big Dig—a much less dramatic box-girder structure that allows the Zakim to be seen up close but from an outside perspective.)

Our tour continued through the southbound tunnel, through areas in which parks and other public areas will be built over the tunnels as soon as the old green monster superstructure is disassembled, a process that had already begun. This will at the same time open up a new greensward through downtown Boston that will bring welcome sunshine to streets so long shadowed and visually oppressed by the rusting elevated hulk of a highway.

As had been our plan, after my talk that evening my guide drove me back to the hotel. We began driving in the general direction of the central artery, knowing that we had to intersect it as we drove toward the harbor. We expected to see signs directing us to an entrance to the new tunnel, but they were nowhere to be seen. (I have never found driving around Boston hospitable to the uninitiated.) Since my guide, who lives in Cambridge, does not frequent the downtown area, he could not be expected to know where the entrances were. We ended up being caught in a vicious loop of one-way streets that we exited when we spotted the old green monster. It gave us a landmark that we followed to the Sumner Tunnel to the airport.

The old tunnel looks old. Compared to the Ted Williams, it is narrow, dark and dirty. In fact, after driving through the new tunnels of the central artery project, as critical as I was of them, I recalled them as wide and bright compared to this old tunnel's confining and depressing feeling. It was only on this last leg of my guided tour through the routes through Boston and on to the airport that I realized how much of an improvement the new tunnels are—even with their imperfections. When I returned to my hotel room, I looked back across the harbor and admired the Zakim Bridge's cables and pylons bathed in blue light—the latter topped with blinking red—and the great project that the signature structure symbolizes.

Acknowledgments

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