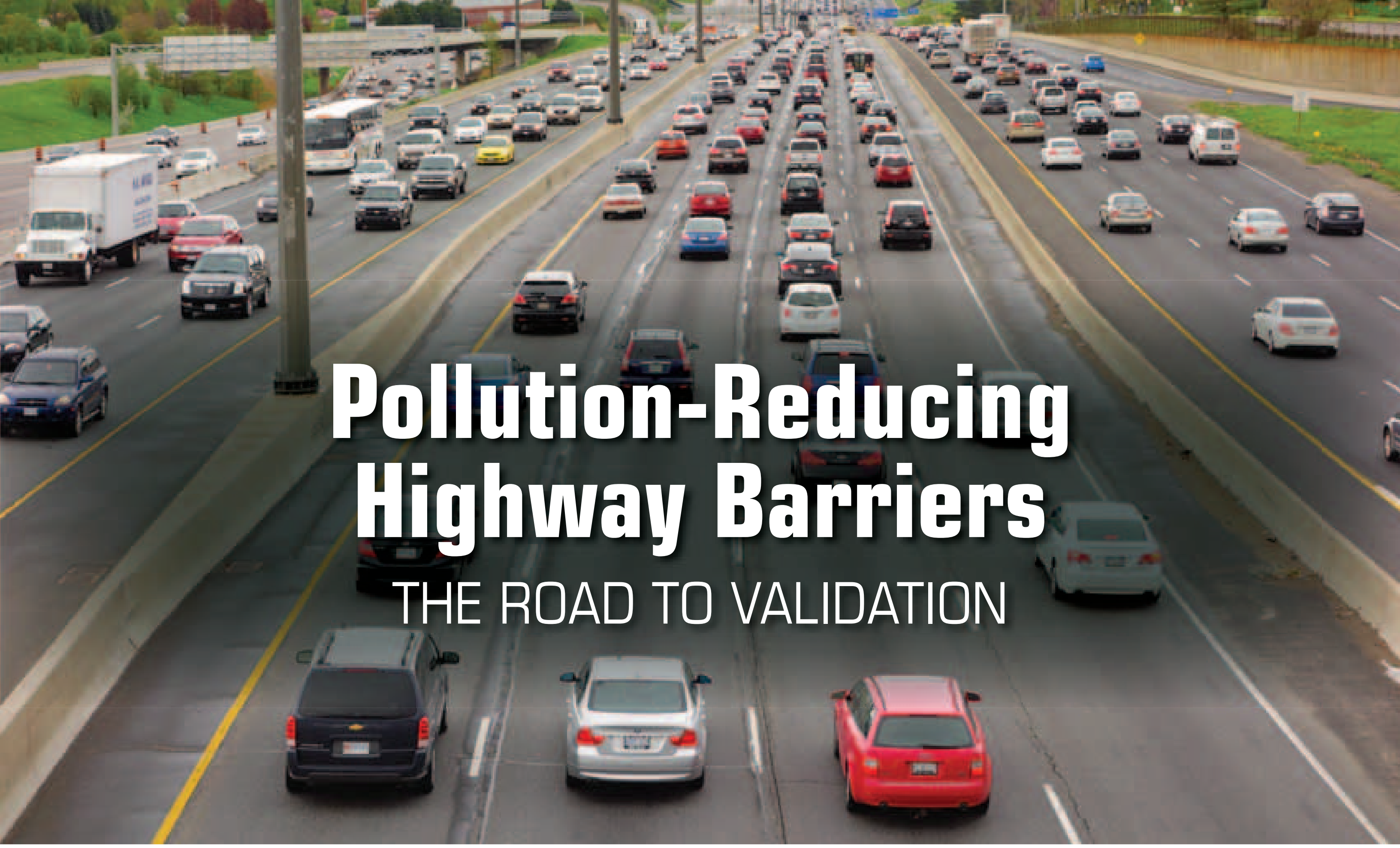
Pollution-Reducing Highway Barriers

THE ROAD TO VALIDATION



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Above: Carrying more than 340,000 vehicles a day, the stretch of Highway 401 that traverses Toronto, Ontario, Canada, is North America's busiest roadway. And with anywhere from eight to 14 lanes across, it is also the continent's widest.

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A new type of highway barrier is addressing one of the biggest sources of urban air pollution: traffic emissions. By incorporating "pollution-eating" photocatalytic coatings, these barriers break down the harmful compounds created by burning gasoline and diesel, as well as mitigate traffic noise. And because these photocatalysts are activated by sunlight, the barrier's extra pollution-eating benefit costs nothing to operate.

However, as several trials have revealed, simply painting a conventional barrier with a photocatalyst doesn't work. This article examines the crucial role of aerodynamics, the shortcomings of using titanium dioxide (TiO_2, currently the most common photocatalytic coating), and what it takes to bring emerging alternatives to market.

The Double-Walled Design

The University of Guelph first got involved in this area in 2011, when air quality consultants Scott Shayko and Xin Qiu approached the institution with a design concept for a novel, double-walled barrier to disperse traffic pollutants. They were looking for help to refine the aerodynamics and test the barrier's performance.

The university's research office put them in touch with the Air Quality Lab, since the lab team had expertise in air quality and in fluid dynamics. Working closely with Shayko and Qiu, the team assessed and tweaked the barrier's configuration. The end result featured an angled baffle on the top of the barrier that faced the highway and directed traffic emissions between the two walls (Figure 1). Thanks to high pressure on the traffic side of the barrier and low pressure just behind the barrier, emissions naturally flow between the two walls and out of a gap at the base of the rear wall. Meanwhile, any emissions that flow over the wall are disrupted by the baffle, which generates vortices that enhance dispersion of pollutants. The process is entirely passive, with no fans or blowers required.

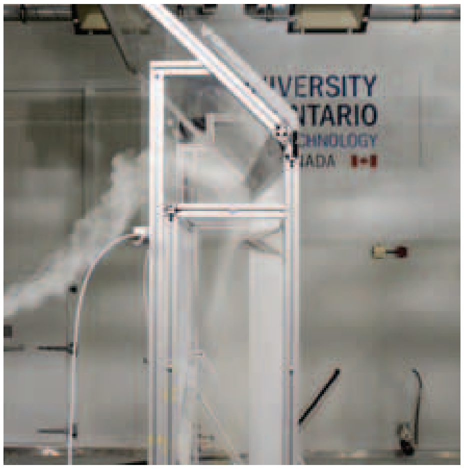

Photo: Xin Qiu, EnvisionSQ

The barrier's angled baffle directs pollution between the two walls, which ensures contact with the photocatalytic coating.

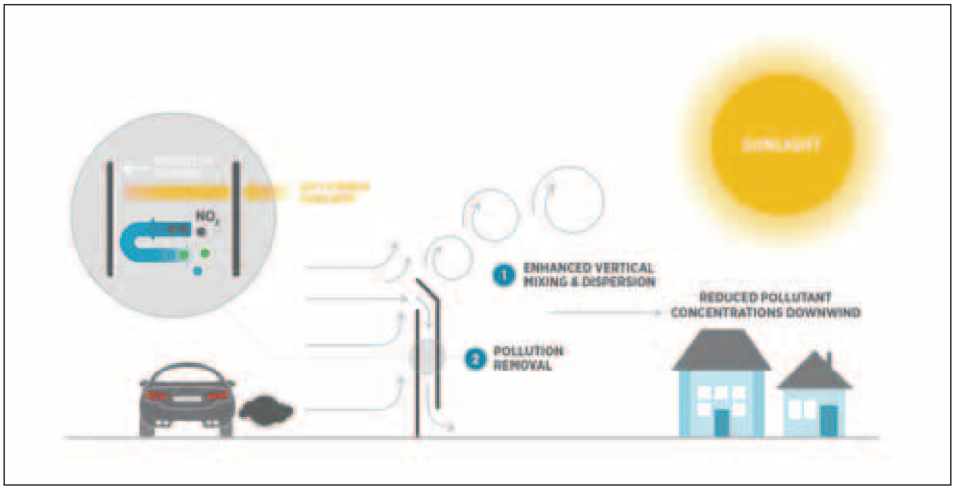

FIGURE 1 **The barrier reduces traffic pollution in two ways: using aerodynamics to disperse pollution and a photocatalytic coating to break down pollutants.**

The research team tested the design using a small-scale prototype at Western University's boundary layer wind tunnel in London, Ontario, which mimics the dynamic and turbulent character of natural wind. Using ethane as a tracer gas to simulate traffic emissions, researchers compared the double-walled barrier against a standard highway noise barrier. Hydrocarbon analyzers measured the concentration of ethane downwind to compare dispersion patterns.

When wind speeds were just 2.5 meters per second (conditions that contribute to high pollution levels), the double-walled barrier reduced downwind concentrations of ethane gas more than 50 percent compared with a standard, noncoated noise barrier (*1*).

As the computational fluid dynamics (CFD) modeling predicted, the vortexes of air created by the barrier pushed the plume of emissions up into the atmosphere. This action increases the vertical height that the plume travels before it reaches residents who live nearby. The further it travels, the more diluted it becomes, reducing the impact on communities.

Shayko and Qiu continued to develop and commercialize the barrier. However, they were not satisfied with simply dispersing traffic emissions. Because their ultimate aim was to actually break down the pollutants, the research team started looking at different options.

Initially, the team discussed the possibility of using electrostatic precipitators to remove particulates from the air. However, that would require a source of electricity, which was not practical. The team then turned to the idea of a sunlight-powered photocatalyst that could break down pollutants—including nitrogen oxides (NO_x) and volatile organic compounds (VOCs)—that contribute to local and regional air pollution.

The Promise of Photocatalysts and the Real-World Results

Certain light-activated catalysts have the ability to break down air pollutants. The best-known of these is TiO_2. Over the past few decades, lab-bench experiments have shown that when TiO_2 is exposed to ultraviolet (UV) rays, it generates strong oxidizing agents called hydroxyl radicals that can break down NO_x and VOCs.

The discovery created lots of excitement about the potential of passively reducing ambient air pollution by coating nearby surfaces with the photocatalyst. The idea is very attractive: paint building exteriors, highway barriers, and even pavement with TiO_2 (or incorporate the photocatalyst into the building materials themselves), and then stand back and watch pollution levels drop.

Although laboratory tests and simulations were very promising, real-world TiO_2 results have been mixed. A study in Manila showed that coating outdoor surfaces with photocatalyst paint could achieve average NO_x reductions of 10 percent significantly less than the numbers seen in lab tests (*2*).

In Europe, the EU-funded PhotoPAQ project tested commercially available TiO_2 products in artificial street canyons designed to mimic roadways with buildings on either side. When the researchers compared NO_x levels in a canyon coated with TiO_2 to those in the uncoated control, the difference was a mere 2 percent.

Similarly, in trials conducted by Germany's Federal Highway Research Institute, applying a TiO_2 coating to a kilometer of highway noise barrier on a six-lane stretch of the A1 Autobahn achieved only single-digit reductions in NO_x compared with an uncoated control. The biggest reductions were on the east side of the highway and were likely due to the prevailing airflow, which directed pollutants towards the eastern barrier (*3*).

Meanwhile, researchers at the University of Texas at Austin's Center for Transportation Research compared coated and uncoated barriers at a toll plaza on State Highway 45. After analyzing more than 230 days of data, they found no consistent reduction in NO_x levels (*4*).

Studies have shown the reasons for this lack of anticipated performance in real-world

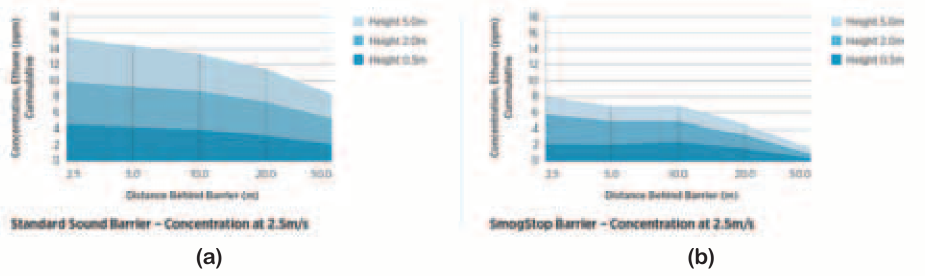

FIGURE 2 Wind tunnel tests reveal that—compared with a standard highway noise barrier (*a*)—the aerodynamic design of the uncoated SmogStop barrier (*b*) significantly reduces downwind pollution levels.

FIGURE 3 TiO_2 catalyzes a reduction reaction that can produce harmful byproducts and create a hard scale on the surface of the photocatalyst (*a*). In contrast, SmogStop's reduction reaction produces harmless nitrogen and oxygen gas (*b*).

situations are twofold: poor aerodynamics and the inherent limitations of TiO_2.

Shortcomings of First-Generation Pollution Barriers

For any photocatalytic surface to work, it has to have sufficient contact with the pollutants it is designed to break down. As several experiments reveal, the flat vertical surfaces of conventional barriers prevent natural airflow from achieving adequate contact (*5*). As air flows over a typical roadside noise barrier, large recirculation zones form in front of and behind the wall and force the air to move upwards. As a result, most of the pollution flows over the barrier and very little contacts its surface. Even more fundamentally, when air flows smoothly along any flat surface, there is a no-slip layer of air right next to the surface that does not move. In the case of a photocatalytic surface, this no-slip layer inhibits much of the polluted air from contacting the photocatalyst.

Based on CFD modeling and wind tunnel results, the research team knew that the double-walled design addressed this issue by enhancing air mixing between the two walls, where it would have plenty of opportunity to contact a photocatalyst on the inner surface (Figure 2). Meanwhile, the turbulent flow created between the two walls disrupted the no-slip layer. However, the team still had to address the shortcomings of TiO_2, which contributed to the disappointing results reported for first-generation photocatalytic barriers.

One problem with TiO_2 is that the reactions in the oxidation pathway it triggers do not fully break down all the pollutants. Instead of turning bigger molecules into their most basic components, they produce intermediate compounds that can be more harmful than the original pollutant. Those compounds include harmful substances such as cancer-causing formaldehyde (*6*). Moreover, TiO_2 can produce nitrate radicals that undergo further light-activated decomposition to form smog-producing ozone (*5*).

Humidity also impairs the performance of TiO_2 because water molecules in the air can block active sites on the surface of the photocatalyst (*7*).

But perhaps the biggest issue with TiO_2 is the dramatic drop in performance over time. One of the products of TiO_2-catalyzed reactions is nitric acid. It can react with basic gases in the air to form nitrate salt (*8*). Over time, nitrate salt creates a hard scale that renders the coating ineffective (Figure 3). For example, one Hong Kong study reported an 80 percent drop in NO_x removal after panels coated with TiO_2 were exposed to an outdoor environment for several months (*9*).

Creating a Different Kind of Photocatalyst

To find an alternative without those shortcomings, Shayko and Qiu's company, EnvisionSQ, worked with the University of Toronto to develop a proprietary photocatalyst that leveraged reduction reactions rather than the oxidation pathway of TiO_2.

This fundamentally different chemical approach prevents the formation of nitrate salts. It transforms NO_x into harmless nitrogen gas and oxygen gas—the basic components of air—and breaks down VOCs into carbon dioxide and water. Without the formation of the nitrates that cause scale buildup, the surface of the photocatalyst remains active and continues to remove pollutants efficiently hour after hour and month after month.

It took several years to hit on the right formula, but eventually the team succeeded. At that point, EnvisionSQ returned to the University of Guelph with the next

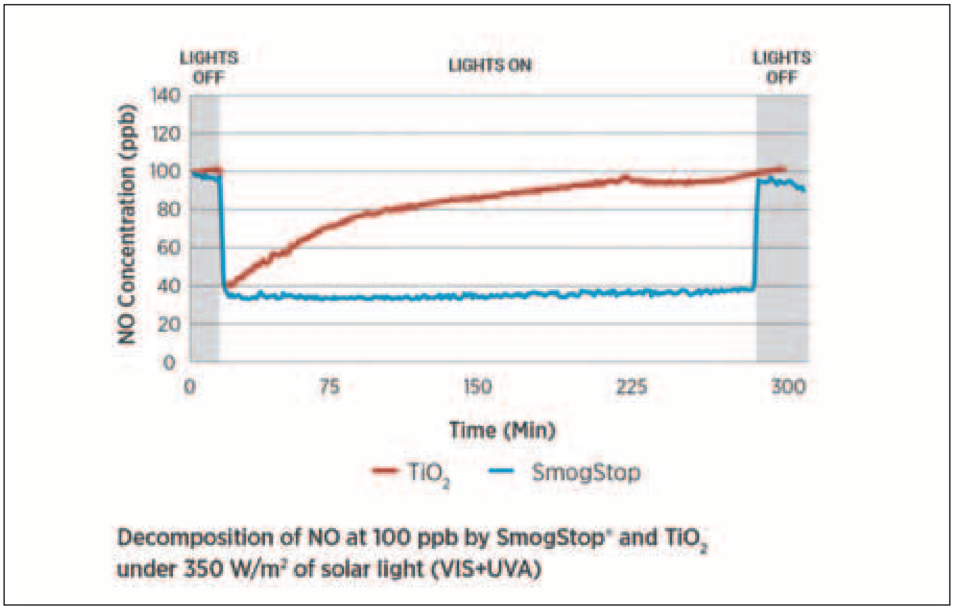

FIGURE 4 **In lab tests, SmogStop reduced NO_x levels further than TiO_2 and continued to perform effectively over the duration of the test, while the performance of TiO_2 dropped significantly.**

challenge: find a way to attach their new photocatalyst to the interior of the barrier. It was not a trivial problem.

The coating had to stick reliably to the barrier's acrylic surface in the face of a broad range of weather conditions: sun, wind, snow, salt, and temperatures ranging from –20°C to +30°C. But simply mixing the particles with adhesives and slapping a layer on the barrier was not an option; researchers also had to make sure they did not block the active sites of the photocatalyst's nanoparticles. It took hundreds of trials to find the right balance between adhesion and pollutant break down, and the team has continued to refine the coating as they have moved from small test samples to full-scale barriers.

To test the coating's effectiveness, the researchers conducted a series of experiments that followed the ISO 22197-1 protocol for photocatalysts. Although the laminar flow conditions specified in the ISO standard do not reflect real-world conditions, using this widely accepted benchmark allowed the team to compare the performance of the barrier with commercial TiO_2 coatings. It also allowed the researchers to assess the improvements they made to the photocatalyst formulation and the coating procedure.

The process involved placing glass plates coated with a photocatalyst into a chamber and then passing nitric oxide over them. To activate the photocatalysts, the Guelph team simulated natural sunshine with an intensity of 350 watts per square meter (Figure 4). This was considered a worst-case scenario, representing the average daytime intensity of sunlight during the month of January in Toronto, when solar intensity is at its lowest.

Over the five-hour test, SmogStop proved 3.6 times more efficient than titanium dioxide and continued to work with no loss of performance throughout the experiment. In contrast, the TiO_2 performance quickly decreased. By five hours, it had stopped working (*10*).

In part, this was because TiO_2 is activated by UV light, which accounts for only 4 percent of total solar energy. In contrast, SmogStop takes advantage of both the UV and visible light spectrum, allowing it to take advantage of a much bigger source of energy.

In a different set of experiments, the Guelph researchers assessed the durability of the barrier's coating in outdoor conditions. Samples of the photocatalyst were placed in a Weather-O-Meter machine, which simulates long-term exposure to light, moisture, and oxidation. At set simulated time durations, samples were removed from the Weather-O-Meter and tested using the ISO protocol to assess how well they reduced pollution levels. The results showed very little—if any—drop in performance, even after the equivalent of 10 years of weathering and use.

Putting It All Together

At this point, the Guelph team returned to the wind tunnel to see how well the coating performed on the barrier. First, the researchers ran smoke visualization tests in the University of Ontario Institute of Technology wind tunnel, which confirmed that the double-walled design channeled emissions between the two walls and created sufficient contact with the coated interior surface.

Next, the team injected NO_x gas into the barrier and then used artificial sunlight to trigger the photocatalytic reaction. Because this was a climatic wind tunnel, the researchers could adjust the amount of solar radiation to simulate actual operating conditions. When the team measured pollution concentrations at the barrier's outlet, they saw NO_x levels reduced up to 37 percent (*11*).

But to truly convince transportation authorities, governments, and other prospective customers that the barrier was effective, the researchers still had to answer a fundamental question: how does it hold up in the real world?

To find out, the team set up field tests in collaboration with the Ontario Ministry of Transportation. In March 2017, they erected a 15-meter segment of the barrier in Toronto along the north side of Highway 401, North America's busiest highway. Each day, more than 340,000 vehicles drive this 14-lane stretch of freeway (*12*).

The barrier was equipped with sampling heads to measure NO_x in the air entering and leaving the barrier at one-minute intervals. From August 18, 2017 to

Photo: Xin Qiu, EnvisionSQ

Smoke visualization tests revealed that the aerodynamics created by a standard noise barrier move pollutants over the barrier, preventing contact with the barrier surface.

February 28, 2018, researchers tracked those levels using data-logging equipment and gas analyzers housed in a trailer set up just behind the barrier. An anemometer installed on the barrier allowed us to measure wind speeds. For other meteorological data, the team relied on a weather station at the nearby Toronto Pearson International Airport. From the data collected, the team calculated the difference between inlet and outlet NO_x concentrations, which provided them with the efficiency of the barrier's pollutant removal.

The study was not without its share of hiccups. For the first several months of the field tests, there was a gap in the existing wall of conventional sound barriers directly west of the SmogStop segment. This unfinished section allowed air to escape around the side of the barriers, reducing the volume of emissions being treated. In December, the Ontario Ministry of Transportation extended the wall, which dramatically improved aerodynamic performance.

Because of that complication—and since the tests ran during the autumn and winter, when daylight is limited in Canada—the pilot results are likely conservative. Still, the findings were impressive.

Strong Results Drive Big Opportunities

In the daytime, the barrier reduced NO_x levels an average of 49 percent. During peak daylight hours, it could achieve reductions of up to 92 percent. Meanwhile, thanks to illumination from the highway's high-mast lighting, the barrier even functioned after the sun went down, although removal rates were less than half the daytime rates. (It is also worth noting that ambient NO_x levels are much lower at night.)

When these results are extrapolated, they suggest a single kilometer of the barrier can remove 43 kilograms of NO_x over the course of a day—the equivalent of taking 200,000 vehicles off that stretch of road.

Meanwhile, the field test also proved that the coating could withstand abuse from nature, backing up the Weather-O-Meter test results. For six months, the barriers endured rain, snow, ice, and high winds, as well as road salt, dust, and more with no loss of performance.

Developing any new technology is a long and complicated process, but the project presented particular challenges. This was uncharted territory in many ways, from the novel aerodynamic design of the barrier to the proprietary photocatalyst developed to overcome the limitations and drawbacks of TiO_2.

Photo: Xin Qiu, EnvisionSQ

In March 2017, the research team and a crew from the Ontario Ministry of Transportation installed several panels of SmogStop barrier along the north side of a 14-lane stretch of Highway 401, the continent's busiest highway.

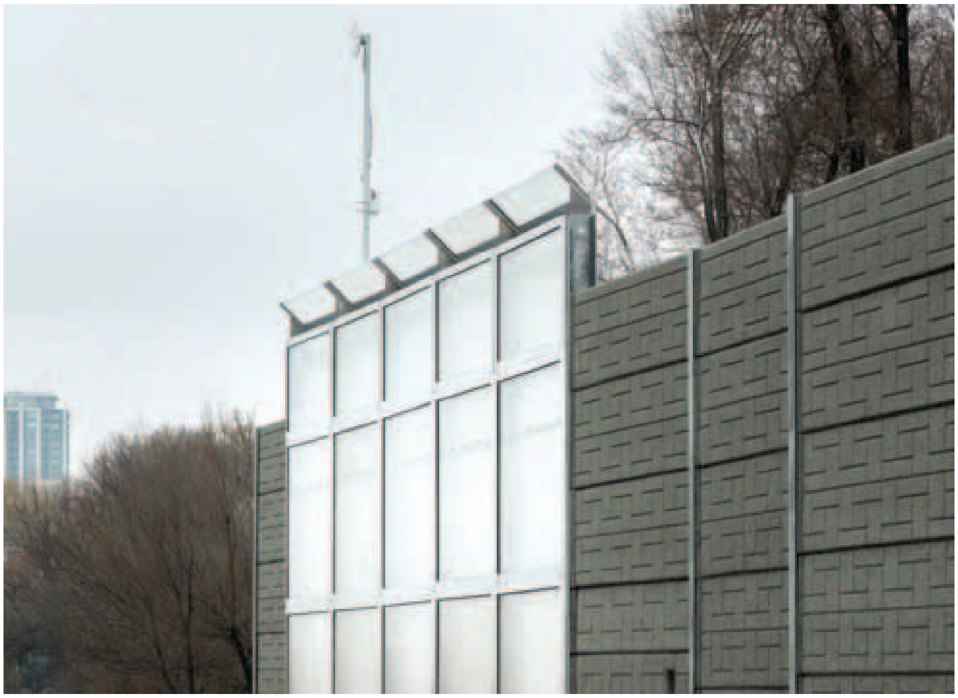

Photo: Xin Qiu, EnvisionSQ

Field tests showed that SmogStop cuts NO_x levels in half during the day, and the energy provided by high-mast lighting created significant NO_x reductions at night.

Over the past nine years, the researchers have continued to iterate and refine both aspects. They also refined and expanded their CFD model, which can now handle very complex flow configurations.

The team proved that this approach works, and they look forward to the day when emission-reduction barriers line highways around the world, creating measurable improvements in urban air quality.

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