Reducing the Carbon Footprint of America's Roadways

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Smog Eating Roads

A Better Way to Get There

Low Emission Asphalt (LEA)

Pathway to Negative Carbon Road Systems

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Real Results.

Low Emission Asphalt (LEA)

Michael Durante, ENV SP

The road construction industry will play a crucial role in our society's goal to reduce carbon. America alone has seven million lane miles of paved road, enough to drive oneself to the Moon and back more than fifteen times. Pavements also cover more than one-third of the ground area of our major cities. The maintenance of that roadway- system[1] requires in excess of 350 million metric tons[2] of virgin asphalt annually and its demands are as endless, as they are insatiable. Roads are necessary as they are the primary infrastructure supporting the logistics underpinning our $30 trillion economy.

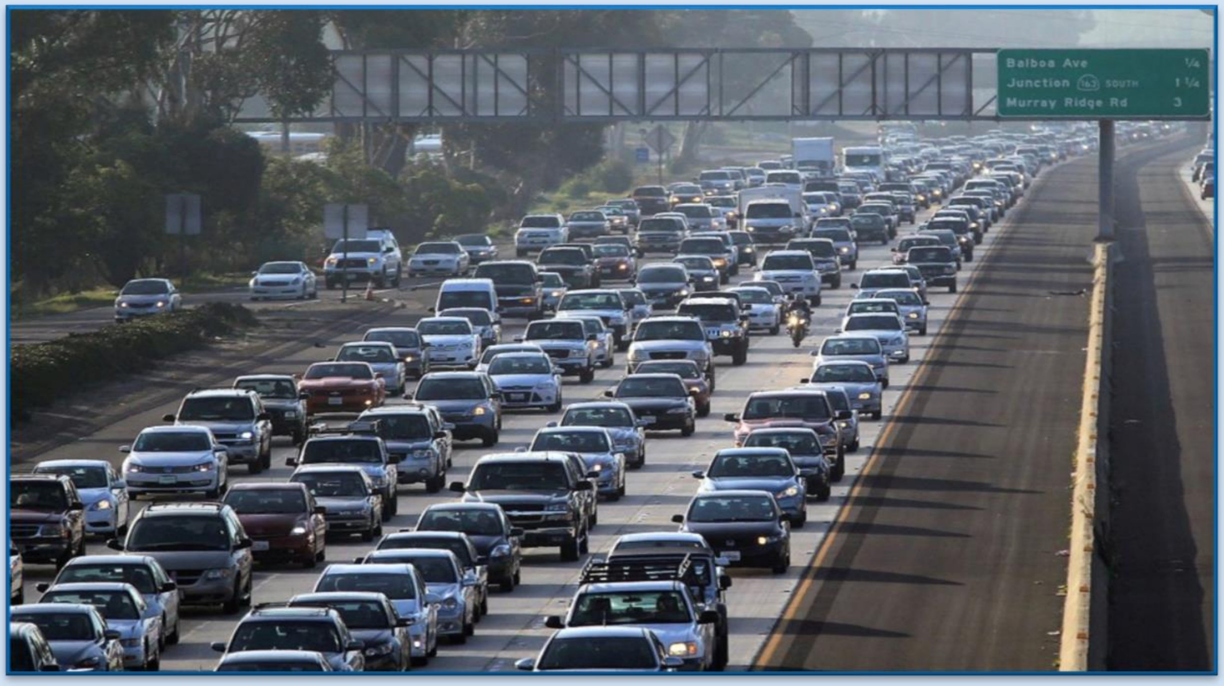
Two Budget Paradigm

The weighted average life cycle (LCA) of the U.S. roadway system is a mere 12 years,[3] worth in net present value (NPV) well over $2 trillion in replacement cost. If agencies and taxpayers do not already struggle to meet this perpetual financial burden, the NPV of the system's ***carbon footprint*** just for maintenance (embodied

[1] Ninety-four Percent (94%) asphalt: U.S. Department of Transportation, Federal Highway Administration (FHWA).
[2] FHWA and National Asphalt Paving Association (NAPA).
[3] National Center for Pavement Preservation at Michigan State (NCPP); FHWA; and NAPA.

carbon)[4] approaches another $100 billion in carbon equivalents (CO_2e)[5] before the added carbon cost of the cars and trucks that traverse it. Adding on-road vehicular pollution, totaling 1.6 billon metric tons annually,[6] the NPV of our road systems' CO_2e jumps to at least $600 billion. $600 billion being the minimum present value of necessary offsets to get to zero carbon.

Airports will spend another $150 to $200 billion in maintenance over the next decade and contribute three hundred million metric tons of CO_2e annually requiring $150+ billion in carbon offsets.



Most agencies have only a financial budget to meet today. In the near future, however, its increasingly predictable that agencies will face a self-imposed or even regulated carbon budget too.

Covering these twin "nuts" will challenge these agencies beyond anything public servants have ever been-tasked to manage in history. It will require imagination, innovation, perseverance, and commercial partnering on par with the ***Space Race*** to be comparably conservative. The paving industry must adapt if we are to support

[4] Embodied carbon means all the CO2e emitted in producing materials.
[5] Paris (Climate) Agreement 2030 carbon pricing model [$50-100-tonne CO2e]; U.S. H. R. 763 – Energy Innovation and Carbon Dividend Act of 2019; prevailing market rates.
[6] U.S. Environmental Protection Agency (EPA); FHWA.

our public works clients. Agencies and industry participants who do not heed the call will fall far behind.

Damage Function Approach

What economists and environmental scientists have begun to focus upon is the notion of a *damage function approach* to air quality and public transportation. In the United States, we spend about $65 billion[7] a year on air quality, but that equates to only 0.20% of gross domestic product (GDP) and far less than one-tenth the estimated economic costs of poor air quality, primarily health and productivity losses.[8]

Regulations have cut air pollution by 20%[9] since the 1970's, yet the number of Americans exposed continues to rise due to urbanization. Today, over 40%[10] of us (>150 million Americans) live in counties with unacceptable levels of ozone contaminations that exceed **National Ambient Air Quality Standards (NAAQS)**. Balancing industry sector contributions to the economy and their respective environmental impact is a challenge. Road systems are both necessary and costly to both budgets. Market-driven pricing for carbon may be the only viable solution to this growing economic disequilibrium.

The "voluntary" carbon credit and quasi-voluntary or "carbon allowance asset" markets (Figure 1) are illiquid and price discovery remains inefficient. But the market(s) are growing rapidly, doubling every 18 months in recent years.

To put the burgeoning combined carbon credit, allowance, and futures markets into perspective, total notional value traded between 2016 and 2019 (pre pandemic) was less than $200 billion globally (<1% global GDP). The market value of Bitcoin (BTC), by comparison, recently reached $1 trillion. California leads the United States carbon credit market with $5 billion in recent transaction volume. Europe leads with over $100 billion. So, we are already falling behind.

Verification of carbon "offsets" has been the primary limiting factor, where less fungible alternative currencies are more speculative (than need) with blockchain technology as the pseudo verification standard.

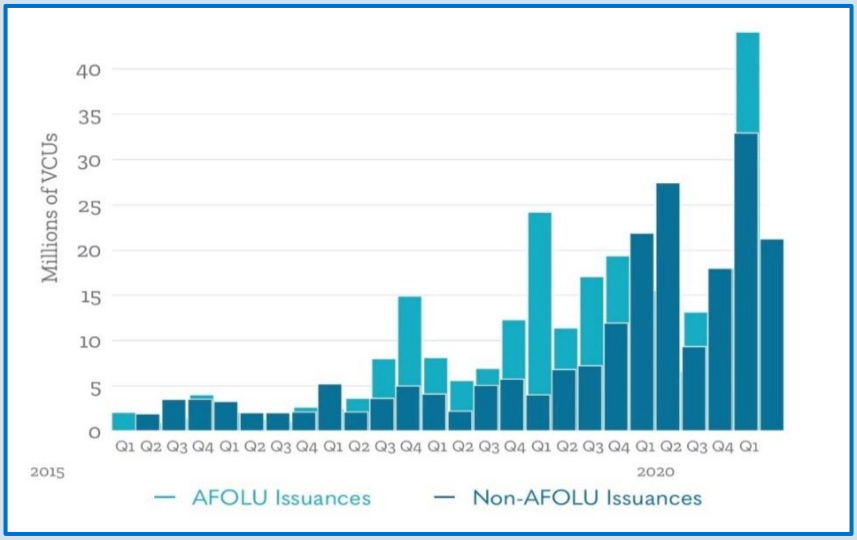
[7] Carnegie Mellon University.
[8] World Economic Forum; Federal Reserve Board.
[9] EPA.
[10] EPA *Our Nation's Air: Status and Trends* report 2019; American Lung Association.

Figure 1 – Prevailing Carbon Credit Prices – Capital Markets [11]

Source: stockcharts.com

Global carbon pricing revenue in 2021 increased by 60% from 2020 levels, to around $84 billion.[12] We believe there is great untapped value in carbon credit market(s) as verification efficiencies are coming together amid higher quality, higher impact credits, including infrastructure related, which are expanding rapidly.

Figure 2 – AFLO and Non-AFLO VCO Issuances



Source: Verra Registry www.vera.org

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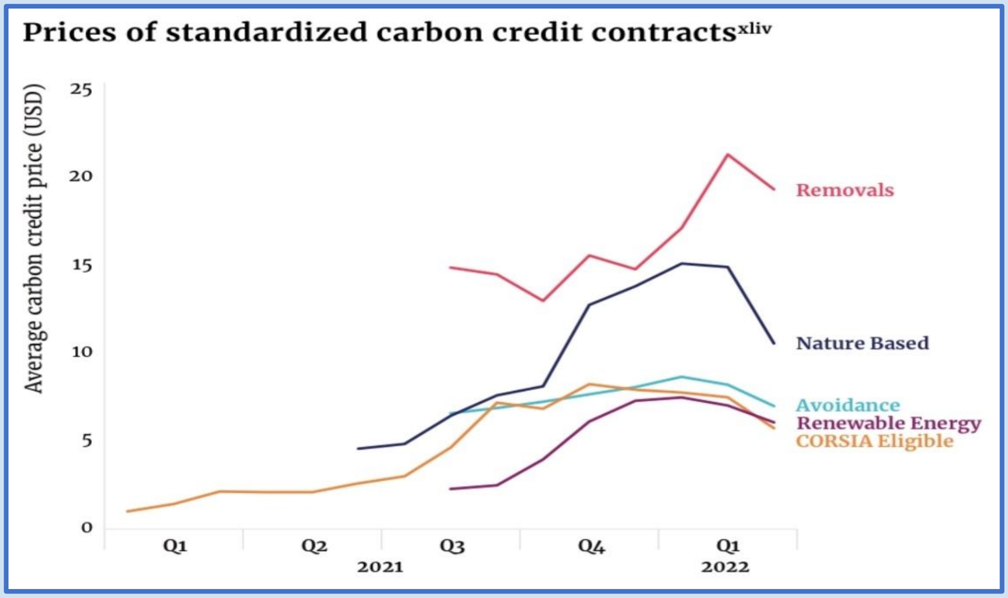
[11] KraneShares Global Carbon ETF www.kraneshares.com/krbn-faq/ is benchmarked to the IHS Markit Global Carbon Index www.ihsmarkit.com.

[12] The World Bank: *State and Trends of Carbon Pricing 2022*.

The non-AFOLU (excludes agriculture, forestry, and land) verified carbon credit (VCO) submarket is now outstripping traditional forestry credits by five to one (Figure 2) while removal-centric strategies are garnering better pricing (Figure 3).

Figure 3 – AFLO and Non-AFLO VCO Issuances – Verra www.vera.org



Source: The World Bank

Further supporting our positive view, one needs only to look at the recent dirge of corporate *net-zero carbon* goals initiated by public firms the likes of FedEx, JetBlue, Disney, Bank of America, among others. Rapid growth of ESG (environmental, social and governance) investment vehicles are driving this sea-change among large, public firms. ESGs are on a run-rate to take-in the better part of a trillion dollars this year.[13]

ExxonMobil's current CapEx budget is 60% allocated to low carbon ventures with little or no near-term revenue and EBIT opportunities owing, in large part, to environmental politics, regulation and ESG influence. Amazon has an active carbon neutral verification program for its vendors[14] and Microsoft charges its operating divisions a carbon fee.[15] All are examples of *de facto* carbon offsets driven and/or measured by financial incentive.

[13] Bunged up: How green bottlenecks threaten the clean energy business, The Economist, June 2021.
[14] Amazon.com: Amazon Aware.
[15] Microsoft Global Carbon Fee | Global | UNFCCC

More aggressive firms including Stripe[16] and Shopify[17] have begun to finance early-stage carbon capture technologies through forward agreements for future carbon reduction credit capacity. Under such structures, the “start-up” exchanges credit capacity from future operations to these buyers for initially non-dilutive, urgent capital.

The risk to the buyer is non delivery, of course. The risk to the seller is that the heavily discounted present price for the expected credit may prove low in the future and hence hinder profitability (dilution by another means). It is, however, a well thought out form of risk capital we view as *value add* to the need to accelerate towards a more efficient carbon allowance market.

So, corporations are likely to become a key funding source for environmentally focused infrastructure projects as corporate boards and managers heed the demands of rapidly changing regulations and investor base with high value offsets.

We believe increasingly more robust carbon pricing markets will give companies, investors, entrepreneurs, and agencies more confidence via direct market signals and that will begin to drive millions of everyday commercial decisions much sooner than most expect.

Solutions

The paving industry has not been idle.

The road construction industry has been searching, for years, methods and practices to cut the amount of energy required to produce hot mix asphalts (HMA). Today, a declining 15%[18] of all flexible pavement resurfacing and rebuilding is done with recycled or so-called reclaimed asphalt pavement (RAP), with variant success.

Here we will discuss prevailing strategies and introduce a potential *gamechanger*.

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[16] Stripe Climate.
[17] Carbon Removal Application Process | Shopify's Sustainability Fund.
[18] FHWA and NAPA.

Warm Mix Asphalt

Warm Mix Asphalt (WMA) is a technique to simply reduce the energy used in asphalt manufacturing. Carbon reductions range 10% to 15%.[19] There remain lifecycle questions related to aggregate adhesion and poor sorptivity, but specialized mix additive technologies to assuage these issues are showing promise.

Polymerized Modified Asphalt

PMAs primarily improve pavement density on high traffic roads and blends contain recycled materials such as *used tires* to help alleviate landfill scarcity. Mixtures, however, are viewed as difficult to pave with due to poor workability and they unfortunately are more energy consuming to manufacture. Compatibility issues raise lifecycle concerns.

Road wear also releases these *plastics*, mainly styrene butadiene styrene (SBS), back into the environment over time, creating air quality and oceanic contamination concerns. SBS from modified asphalts is the third largest source of roadway microplastic pollution.[20]

> *"But [our] concern is if you put [polymers] in the wearing course, that you will create microplastics. One of the significant issues for us is road wear particulates. This has only become a mainstream issue recently, but it is a key challenge for the highway sector."*
>
> **– AECOM**

Reclaimed Asphalt Pavement

RAP involves adding severely aged pavement to blends, of course, so the biggest hurdle is that these admixtures simply do not last long, giving them limited advantage both in terms of cost and carbon relative pure virgin asphalt overlays.

RAP also embrittles unevenly, making interim maintenance difficult. As a result of performance inconsistencies, the **Federal Highway Administration (FHWA)** has been cutting back its RAP (%) guidance (Figure 4).

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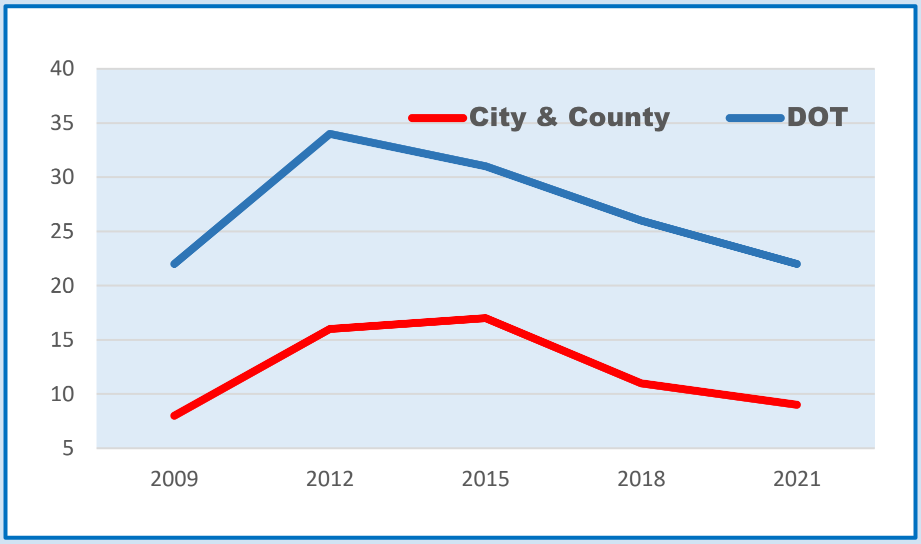
[19] Ingevity; FHWA; NAPA.
[20] Rodland E, *Ecotoxic potential of road-associated microplastic particles (RAMP)*, Norwegian Institute for Water Research, November 2019.

Figure 4 – Recycled Asphalt (RAP)
(In MM tons)



Source: NAPA; FHWA

Cold-in-Place Recycling

CIR is a highly effective way for agencies to lower repaving costs for severely deteriorated pavements as a form of full-depth recycling. The technique can save up to 25% - 35% of the capital outlay of a rebuild and has a positive impact on carbon related to asphalt manufacturing.

Micro-Paving

For worn, high-volume roads, micro (re)surfacing offers an economical, quick fix for rutting damage. These products have limited impact on life-cycle assessment (LCA) and are prone to bonding issues if not of high quality. They are useful for specific stress-related mediation but have limited impact on carbon savings.

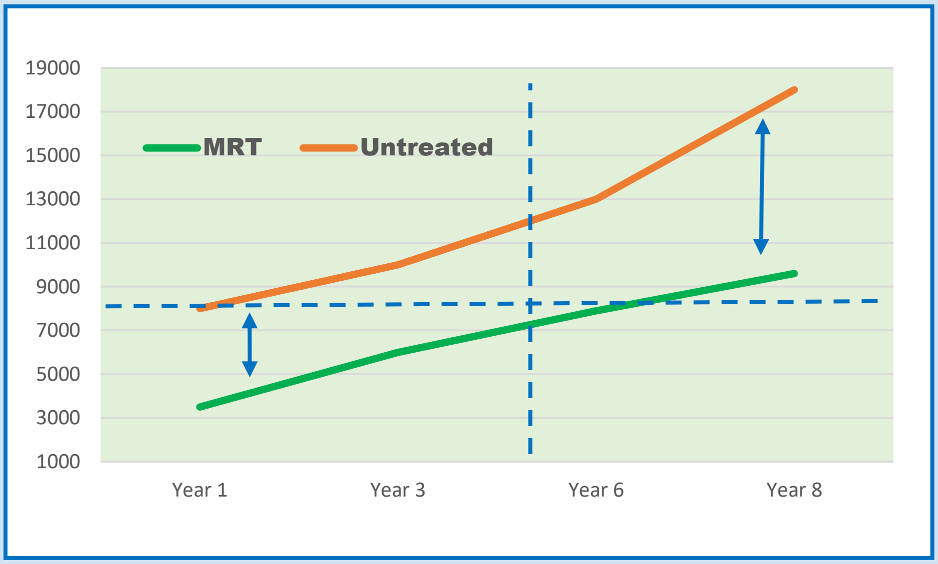
However, there are new post paving penetrant technologies emerging which can "retrofit" micro surfaces with environmentally beneficial properties.

Molecular Rejuvenation

At the road surface, pavement oxidation begins immediately, opening the way for water intrusion and exponential oxidative deterioration of the pavement, the primary factor shortening lifecycles for residential and arterial roads which comprise as much as 77% of pavements.[21] A fifty-year proven approach is to remedy this by spray-applying a natural or maltene-based rejuvenator.

Maltene Replacement Technology (MRT) reintroduces to the aged asphalt binder, exact molecular components (maltene fractions) lost to manufacturing related thermal stress and in-service oxidation, extending pavement life by years (Figure 4),[22] cutting both paving budgets and avoiding asphalt manufacturing emissions by 50% or more by significantly stretching-out repaving cycles.

Figure 4 – Maltene Rejuvenator (Reclamite) Study:
Eight Year Oxidation Rate Curves Charleston County (SC) [23]
(In poises) [24]



Source: Pavement Technology, Inc.; APART

Carbon Budgeting

Current and pending emission regulations are not only making low carbon asphalt solutions attractive, but increasingly becoming mandated. For example, the city council of a large agency customer recently ruled that all public works contracts of a certain value must include ISI Envision (ENV)[25] sustainable infrastructure credits going forward.

[21] American Road & Transportation Builders Association (ARTBA).
[22] Multi-year MRT Sustainability Study: Charleston County (SC): Pavement Technology, Inc.; APART.
[23] Reclamite® is a trademark of Ergon, Inc.
[24] The poise (symbol P) is the unit of dynamic viscosity (absolute viscosity) in the centimeter-gram-second system of units.
[25] Institute for Sustainable Infrastructure (ISI) ENVISION, www.sustainableinfrastructure.org.

We do not think this is an anomaly. ISI is the **American Public Works Association (APWA)** and the **American Society of Civil Engineers (ASCE)** and mirrors the **U.S. Green Building Council (USGBC) LEED** for public works projects. These are fast becoming *de facto* environmental impact self-regulatory organizations (SRO).

So, future public works bid lettings are likely to include emission budgeting, placing increased onus on the paving industry to necessarily assist agencies in reaching their net zero carbon mandates.

Traffic Pollution

EPA technical data shows that as much as two-thirds of atmospheric nitrogen contaminations (NOx), the primary photochemical smog (O_3) precursor making it a leading (third largest actually) [26] greenhouse gas (GHG), are emitted from mobile sources.[27] And nearly half of all Americans live within 'maximum exposure' to near-roadway pollution or within close proximity to high AADT volume roads, according to the most recent U.S. Census.[28]

Types of reactive nitrogen gases have a half-life as high as 100 to 150 years [29] and the EPA believes NOx concentrations from vehicles and near roadways are appreciably higher than those measured at monitors in the current EPA network. In fact, near-road contaminations can be 2–3 times higher than measured at nearby area-wide monitors,[30] making road-level "breathing zones" uniquely attractive targets for managing dangerous tropospheric ozone (O_3) loads.
The American Lung Association has concluded:

"*The burden of air pollution is not evenly shared. Poorer people and some racial and ethnic groups are among those who often face higher exposure to pollutants…"* [31] owing to their sheer proximity to major point-sources (industry, traffic, and airfields) for anthropogenic pollution.

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[26] Dahlmann K. et al., *Quantifying the contributions of individual NOx sources to the trend in ozone radiative forcing,* Atmospheric Environment, February 2011.
[27] EPA: List of Extremely Hazardous Substances, www.epa.gov.
[28] U.S. Census Blocks 2010, U.S. Census Bureau, www.censes.gov; and U.S. Department of Transportation, Federal Highway Administration (FHWA), Average Annual Daily Traffic Data (AADT), www.fhwa.dot.gov.
[29] EPA, Technical Bulletin: *Nitrogen Oxides (NO_x), Why and How They are Controlled*, November 1999.
[30] EPA: Near Roadway Air Pollution and Health, Frequently Asked Questions EPA-420-F-14-014, www.epa.gov.
[31] American Lung Association, *Disparities in the Impact of Air Pollution*, www.lung.org.

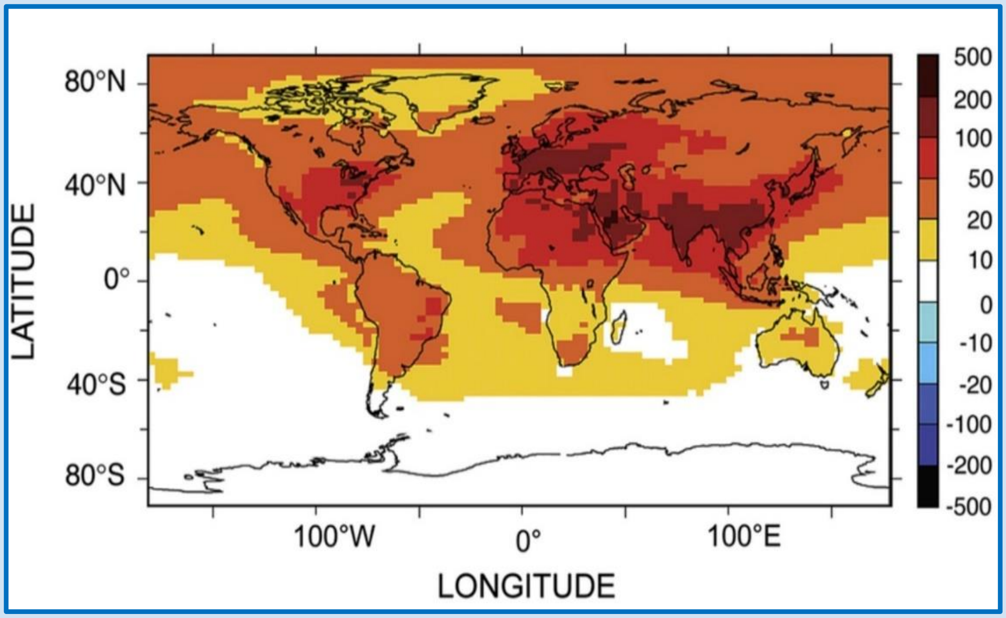
Well observed is the acceleration in NOx contaminations from human activities, of course. It has two related impacts – regional air quality (tropospheric ozone or "smog") and climate change writ large (stratospheric accumulations). O_3 is a dominant GHG associated with positive (warming) radiative forcing (RF) of our climate.[32] The RF of a given pollutant species is how we measure global warming potential (GWP). NOx has a net radiative flux of 0.35 W m^{-2} (watts per square meter) [33], making it the third most impacting on climate change after CO_2 and CH_4 (methane).

Many may be easily confused by the indirect nature of NOx on GHG accumulations and hence incorrectly overlook it. More clarification from the UN's Intergovernmental Panel on Climate Change (IPCC) to address NOx more formally is imminent.

For our transportation sector, it's *act locally to act globally*.

Figure 5 – Atmosphere Radiative Forcing from Road Transportation

Global / Climate



Source: United Nations IPCC

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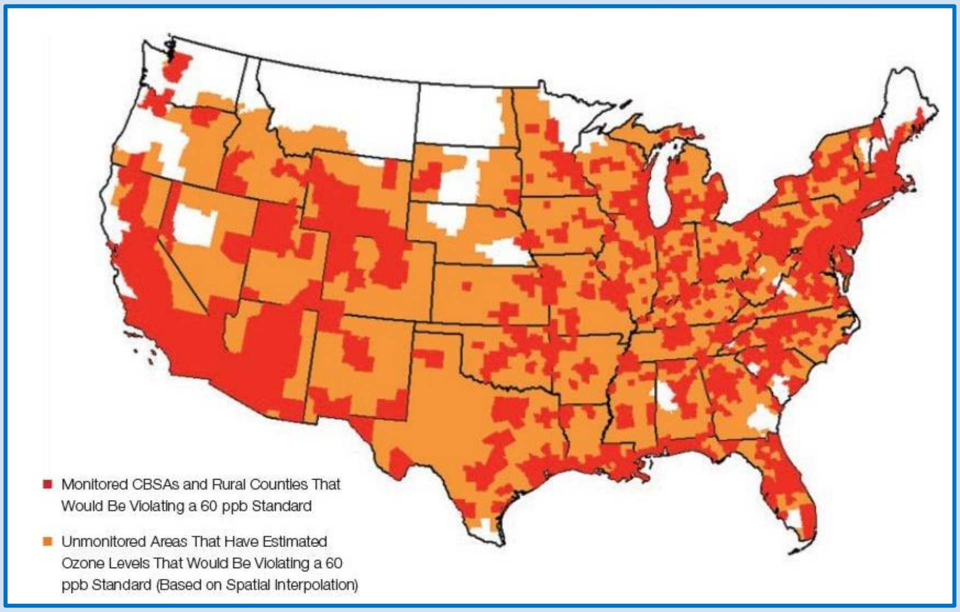
[32] Derwent RG, Radiative forcing from surface NOx emissions: spatial and seasonal variations, Institute for Atmospheric and Environmental Science, University of Edinburgh 2007.

[33] Radiative forcing is the change in net, downward minus upward, radiative flux expressed in watts per square meter at the tropopause (top of atmosphere) due to the change in an external driver of climate change.

Figure 6 – 8-hour Ozone Nonattainment (60 ppb)

Regional / Air Quality



Source: Environmental Protection Agency (EPA)

The Good News is that vehicles are getting more efficient. Average new vehicle fuel economy for **internal combustion engine (ICV)** passenger cars has increased from 13 mpg in 1975 to 25 mpg today,[34] and expected to steadily rise to 40 mpg in the coming decade.[35] Some ICV models already exceed 35 mpg.[36]

The Bad News is that our urban centers and accompanying vehicle ownership are growing far faster than emission technology can pace. America has seen annual new vehicle registrations triple since 1975,[37] far outpacing gains in fuel efficiency.

While **new energy vehicle (NEV)** growth has been steady, wide adoption has been limiting due to steep cost prohibitions, lackluster consumer enthusiasm, and other, more intractable constraints including poor renewable energy scalability and efficiency.[38][39][40] The electric vehicle (EV) market e.g., appears centered exclusively on the super-luxury market, with average MSRPs exceeding $73,000.[41]

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[34] EPA: National Vehicle and Fuel Emissions Laboratory (NVFEL), www.epa.gov.
[35] EPA: Environmental Ratings on the Label, Vehicle Emissions, www.epa.gov.
[36] EPA: Office of Transportation and Air Quality (OTAQ) / National Vehicle and Fuel Emissions Laboratory (NVFEL), University of Michigan, www.lsa.umich.edu.
[37] US Department of Transportation, Federal Highway Administration (FHWA), www.fwha.gov.
[38] MIT Sloan School of Management, *The Real Barriers to Electric Vehicle Adoption*, August 2017.
[39] MediaVillage, *Five Reasons Why Electric Car Sales Fail at the Dealer Level*, June 2019.
[40] Forbes, *Prediction: Auto Industry Headed for Financial Pile-up as EV Sales Disappoint*, June 2018.
[41] Weighted manufactured suggested retail price (MSRP): Edmonds, www.edmonds.com.

There have been 1.7 million EVs sold in the United States since 2010 or about 0.6% of cars and other light duty vehicles on our roads presently.[42] The National Renewable Energy Laboratory (NREL) predicts that energy demand would skyrocket by over 60% [43] from current capacity limits if EV adoption approaches even low-level estimates. Yet, where would we get more electricity today, tomorrow, or even fifty years from now to meet such an enormous increase in electricity demand? Increased California *brownouts* are an early indicator.

By most estimates, we would need at least ten billion new solar panels [44] or more installed and replaced every decade in the United States alone just for electric cars, creating substantial financial, logistic and land use issues. That adds up to about fourteen million acres of repurposed land (25,000 square miles) and in excess of $25 trillion in costs every replacement cycle.

Of course, none of this will matter unless these prospective solar farms will be able to constantly produce the massive amount of electricity needed despite current efficiencies just 15% or less.[45] While future technology must develop much more rapidly to efficiently transfer solar (or wind) power over long distances and store it.

Contrasting beliefs, global energy consumption from renewables (includes hydroelectric and nuclear) has stagnated at 16.4% in 2010 and only 17.1% as of 2019.[46] Energy consumption from fossil fuels was 91% in 1950 and estimates for 2050 are 76%.[47]

Reasoned analysis suggests that even if we solve for such limitations for renewable energy sources, in part or in whole, estimates for overhauling the country's electric grid and energy infrastructure for new energies *ballparks* around a hundred trillion dollars, mostly recurring.[48] [49] [50]

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[42] Argonne National Laboratory, February 2021.
[43] National Renewable Energy Laboratory (NREL), www.nrel.gov.
[44] Glenn H and Ost I, www.pick-my-solar.com; Herron D, www.greentransportation.info.
[45] National Renewable Energy Laboratory (NREL).
[46] Phillips 66.
[47] Ibid.
[48] The Republican Study Committee, *A Greedy New Steel*, February 2019.
[49] The University of Texas at Austin Energy Institute.
[50] Stanford University, School of Earth, Energy & Environment.

There also are troubling environmental and ecological risk related to lithium and cobalt (strip) mining as they expand at breakneck pace to meet rising EV demand, including soil and air contaminations as well as serious water pollution and depletion issues.[51]

A typical EV carries as much as 1,800 pounds of batteries; a typical electric truck as much as 3,000 pounds and discarded Li-ion battery disposal is emerging as battery electrics already create more than 250,000 tons of problematic land fill annually with expectations for a seven-fold increase in the next decade.[52] Only about 2% of lithium batteries are recyclable today.[53][54]

Converting just the State of California to all-electric would consume 100% of the world's known lithium reserves.[55] More than half of all cobalt reserves are in the tiny, troubled country of The Congo. There are clear national security issues as well. China controls 85% of the world's EV battery production.[56]

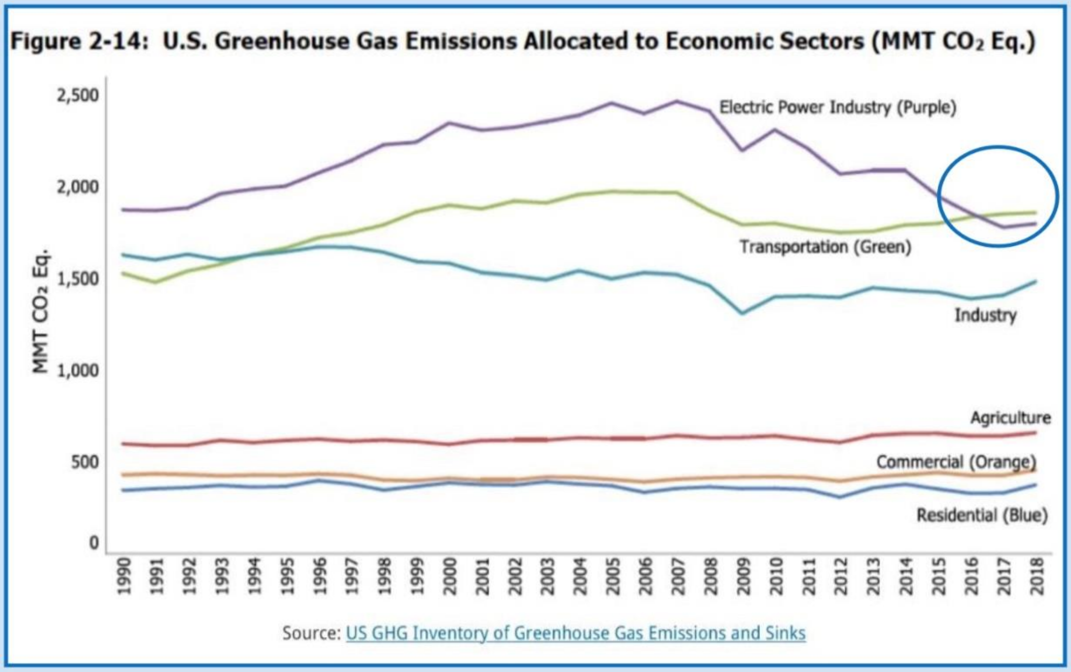
Alternative energy sourcing and transportation type are proving more difficult to scale or even afford financially and environmentally than any of us had hoped.[57][58]

One should value the prospects for NEVs but be prepared that they may become only a part of the solution and require protracted rollout until unintended environmental burden shifting becomes better understood.

Meanwhile, mobile source pollution is the country's number one GHG problem now. Intensifying this, of course, the EPA sets reactive nitrogen at 298 carbon dioxide equivalents and O_3 estimates range from 65 CO_2e (globally) to over 900 CO_2e (regionally), making the removal of vehicular emissions an on-going urgent priority.

[51] Murry J: Is the Nobel Prize-winning lithium-ion battery really having a positive impact on the environment?, *NS Energy*, October 2019.
[52] Calma J, *The electric vehicle industry needs to figure out its battery problem*, The Verge, November 2019.
[53] Murry J: Is the Nobel Prize-winning lithium-ion battery really having a positive impact on the environment?, *NS Energy*, October 2019.
[54] Bunged up: How green bottlenecks threaten the clean energy business, The Economist, June 2021.
[55] Phillips 66.
[56] www.moneyweek.com.
[57] Finkler T and Hannon K, *Renewable Energy: Status and Struggles*, Stanford University.
[58] The Wharton School, University of Pennsylvania, *Can the World Run on Renewable Energy?*, April 2015.

Figure 7 – Greenhouse Gas Emissions by Sector



Source: Environmental Protection Agency (EPA)

Where will agencies be able to go to meet near-to-long term carbon reduction goals? We predict they will target public works projects to turn our built environment into a major part of the solution to ***climate change***. And our industry will increasingly need to address these needs.

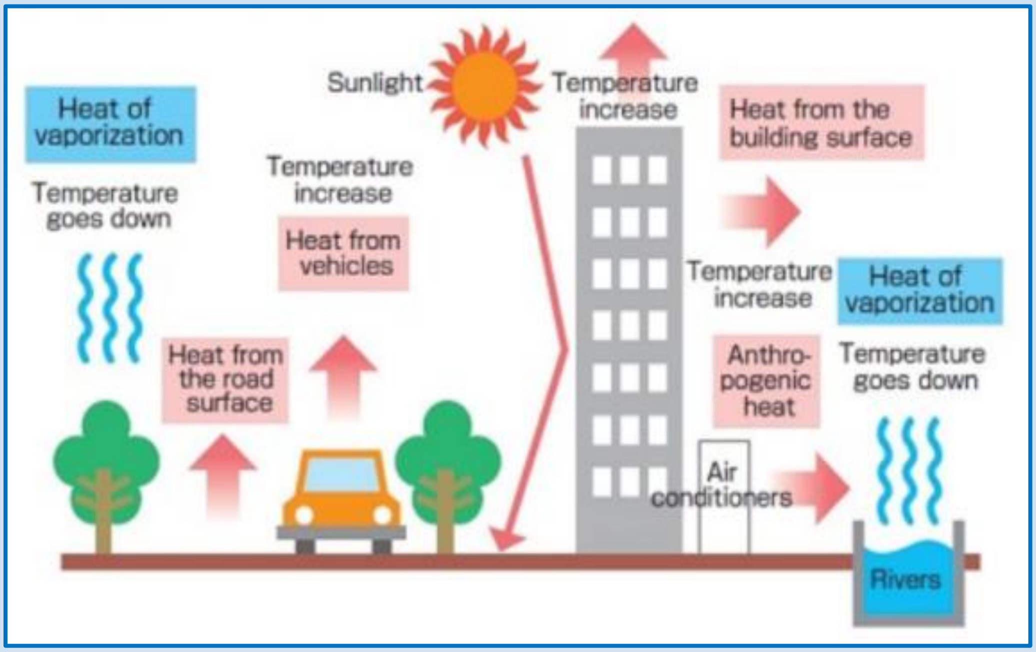
Heat Islands

The environmental issues with roads do not end with manufacturing emissions or even with traffic pollution.

The growth in urbanization and changing land use coupled with ever rising vehicular emissions intensifies the ***Urban Heat Island effect*** **(UHI)** in our largest cities. UHI intensity itself, is highly correlated to air-toxin levels.

Heat-build and poor air quality exaggerate calefactory-related stresses from O_3 levels and accompanying disease in humans, including atopic (asthma) and more serious pulmonary and cardio disorders. Additionally, the number one weather-related cause of death in the United States is heat.

Figure 8 – How the Heat Island Effect Occurs



Source: Green Ribbon Toronto

Though UHI intensity depends on any number of factors, the thermodynamic properties of surface materials like roads amplify the temperature profiles at the local scale. Our cities are heating-up (Table 1). So, roads are a target.

Table 1 – Temperatures Rising & Accelerating Rapidly

Mean Rate of Change (°C / Century)

Since:	1760	1810	1860	1910	1960	1990
California	-	-	0.47 ± 0.26	0.99 ± 0.14	1.76 ± 0.13	0.83 ± 0.39
Contiguous United States	-	0.66 ± 0.25	0.76 ± 0.18	0.87 ± 0.08	2.16 ± 0.16	2.76 ± 0.36
United States	-	0.69 ± 0.24	0.80 ± 0.16	0.89 ± 0.08	2.36 ± 0.13	2.42 ± 0.39
North America	-	0.82 ± 0.23	1.02 ± 0.18	1.11 ± 0.11	2.90 ± 0.19	4.72 ± 0.28

Source: Berkeley Earth

Conventional asphalt paving materials can reach peak summertime temperatures of 150°F [59] or more, transferring excess heat to the air above them and heating stormwater as it runs off the pavement into waterways, effecting watershed ecology.

Pavements in urban centers can be as much as one-third of land cover in major cities.[60] As such, roadway systems play a critical role in environmental planning. Further, asphalt binder begins to experience exponential oxidation at as low as 70°F and hyper-photodegradation at 120°F.[61] Studies have shown that even modest improvement in asphalt temeperature can materially extend the service life of the asset. [62] Researchers at MIT[63] have concluded that lowering asphalt emissivity can have a materially positive effect on near road **building electricity demand (BED)**.

So, there are many reasons UHI is becoming increasingly examined as it relates to paving products, techniques and *best practices*. For UHI, one not need speculate. Future paving-related bid lettings are going to include UHI mitigation. Agency consortias such as the **Global Cool Cities Alliance (GCCA)**[64] have grown rapidly and focus on promoting *heat-reducing* infrastructure strategies. Cities like Los Angeles and Phoenix are already leading the way with actve "cool pavement" paving programs.

The use of "cool pavement" products is expanding rapidly and the Infrastructure Investment and Jobs Act of 2021 (IIJA) includes billions of dollars in cool pavement focused appropriations.

Historically, "high albedo" pavements, which are lighter colored roads, sidewalks and parking lots have been implemented to improve reflectance. But such products are visible light (VL) centric and unable to reflect ultraviolet light (UV). They hence are poor at mitigating pavement emissivity critical to UHI management. These "white asphalts" also tend to be aestethically challenging with poor durability, require signifiant new pavement rebuilding costs, and tend to reduce human comfort levels.

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[59] EPA Heat Island Reduction Program (HIRP): *Using Cool Pavements*.
[60] Lawrence Berkeley National Laboratory, Cool Pavements, www.heatisland.lbl.gov.
[61] Hossain K and Karakas AS, *Effect of Ultraviolet Aging on Rheological Properties of Asphalt Cement*, Memorial University of Newfoundland and University of Illinois, Urbana-Champaign, June 2018.
[62] EPA HIRP: *Using Cool Pavements*, www.epa.gov/heatislands.
[63] Massachusetts Institute of Technology Concrete Sustainability Hub (CSHub).
[64] www.globalcoolcities.org.

Porous pavements can reduce stormwater runoff by alowing rain to pass through the surface, recharging groundwater while reducing flood risk, but do not effectively redirect solar energy and are insuitable for vehicular traffic loads.

An emerging technique is to deploy photocatalyst materials such as titanium dioxide (TiO_2) into roads and roadway materials as the added catalyst is very effective at reflecting UV and reducing pavement emissivity. New testing standards for pavement related UHI mitigation develped by the EPA require low emissivity.

Microplastic Pollution

Newer to the road-related environmental foray are microplastic contaminations. Researchers now equate the extensive use of plastics as akin to creating a global "plastic cycle" on par to other critically *human-intruded* processes such as the carbon cycle. Because people breathe, eat and drink microplastic particles (MPP), their rising levels are alarming given the associated health and ecological risks.

What might surprise one is that as much as 85% [65] of the microplastics that end up in our environment come from roads and are a material contributor to poor air quality and oceanic contaminations. The culprit is cars and trucks as both tire and brake-pad wear are the significant contributors. Scientists have a name for roadway microplastic accumulations or "road-associated microplastic particles" *aka* RAMPs.

Tire-wear particles ($RAMP_{TWP}$) being the largest source along with brake-pad wear ($RAMP_{BPW}$) debris and polymer modified asphalts ($RAMP_{PMA}$) also contributing. All adds new meaning to what happens when the *rubber meets the road*.

Both urban and highway stormwater runoff will collect RAMP, creating a clear pathway for microplastic contaminations from land-based sources to an agency's local aquatic environment and beyond to rivers and eventually our oceans. [66]

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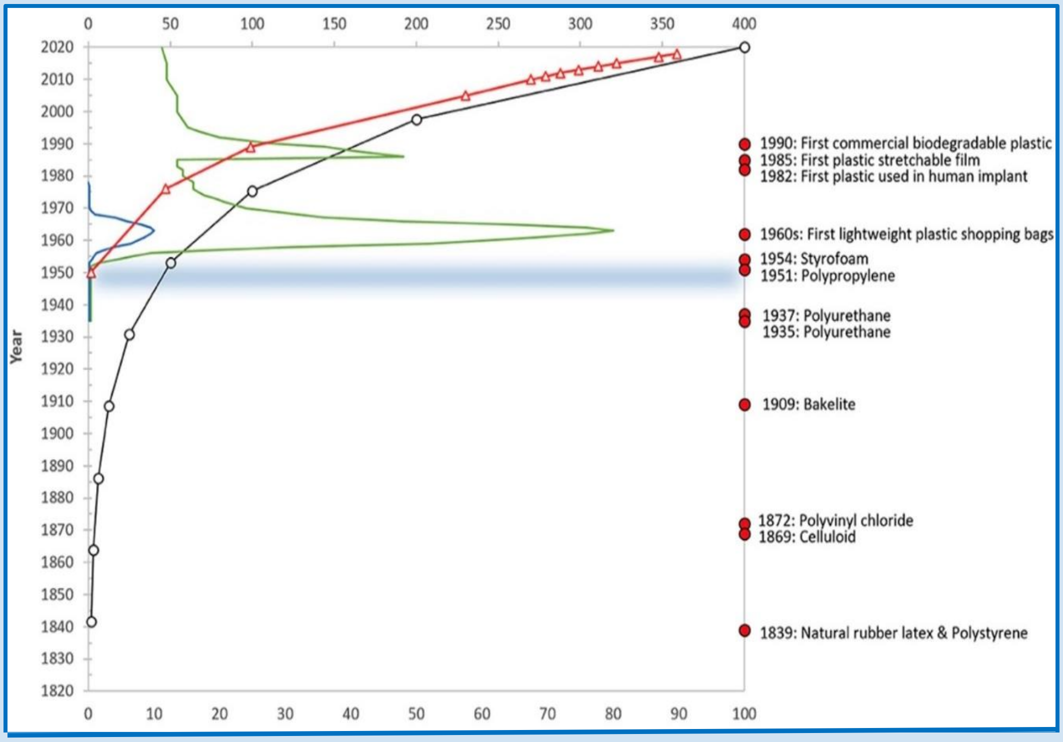
[65] Carrington D, Airborne plastic pollution 'spiraling around the globe,' study finds, *The Guardian*, April 12, 2020.
[66] Liu F, Borg Olesen, et al., *Microplastics in urban and highway stormwater retention ponds*. June 25, 2019.

Stakeholder demand, including almost two hundred countries, is growing for a new global ecological and air quality agreement related to marine litter and microplastic particulate matter $PM_{2.5}$ and PM_{10} accumulations on par with the Paris Agreement. It came-up for vote at the 2021 United Nations Climate Change Conference known as COP26 last November.

Figure 9 – Global Plastic Production
(Millions of tons)



Source: Frontiers in Environmental Science

While one can "value" GHGs (CO_2e) per international agreements like *Paris* right now, we suspect cross-border consensus on MPP is coming soon. A recent study of San Francisco Bay indicated much of the seven trillion particles of microplastic found came from tires.[67]

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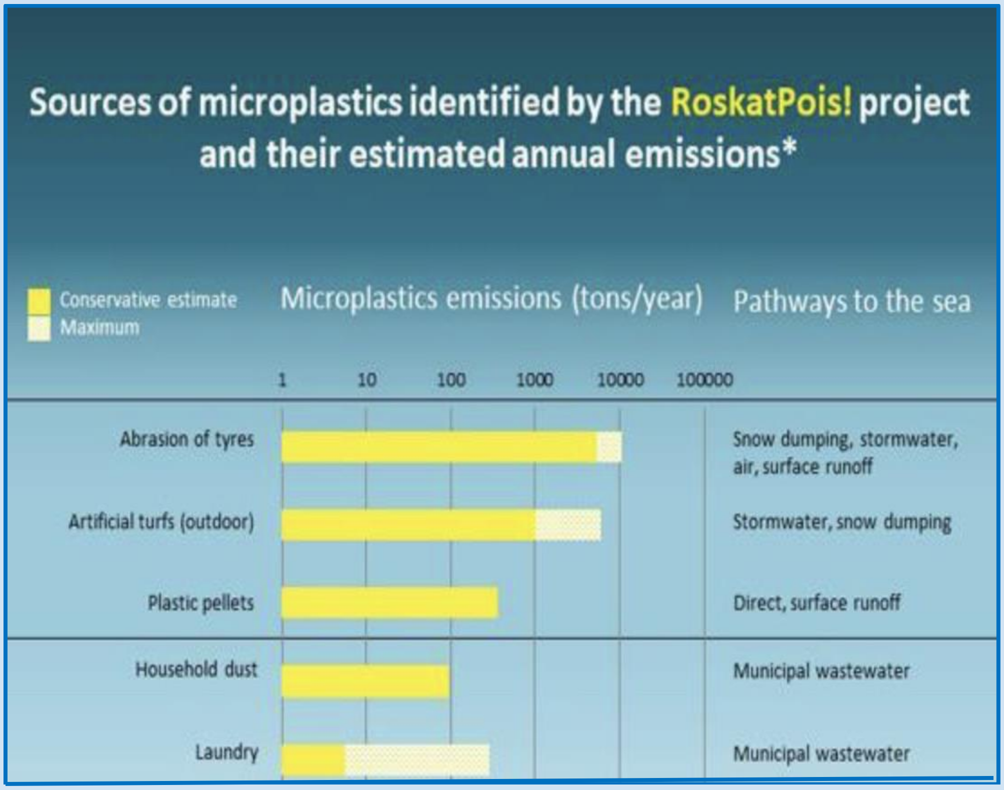
[67] Edelstein S, *Microplastic pollution from vehicle tires is a serious global issue,* Green Car Reports, April 14, 2021; and San Francisco Estuary Institute (SFEI).

Fourteen million metric tons of microplastics have accumulated on the world's ocean floors and hundreds of millions of tons are currently just *floating around*.[68][69] The rest of the road-related MPPs emitted end-up in our air, adding to $PM_{2.5}$ build-up. Roadway microplastic debris factors directly into as much as half of the oceanic accumulations of MPP and more than two-thirds of the ozone contaminations.[70][71]

Figure 10 – Sources of Microplastic Pollution



Source: Finnish Environment Institute SYKE

One thousand tons of microplastic accumulation equates to pulverizing three hundred million plastic water bottles. For every one million cars on our roads, scientists estimate 5,000 tons of TWP is created every year.[72] The U.S. alone has

[68] van Sebille, Wilcox C, et al., *A global inventory of small floating plastic debris*, Environmental Research Letters, Volume 10, Number 12, December 2015.
[69] Liao K, The Atlantic Ocean Could Contain 200 million Metric Tons of Microplastic: Study, Global Citizen, August 2020.
[70] Rodland E, *Ecotoxic potential of road-associated microplastic particles (RAMP)*, Norwegian Institute for Water Research, November 2019.
[71] Mahowald N, Cornell University School of Engineering, Earth and Atmospheric Sciences and Brahney J, University of Utah Environmental Biogeochemistry & Paleolimnology Lab.
[72] Baensch-Baltruschat, et al., Tyre and road wear particles (TRWP) – A review of generation, properties, human health risk, ecotoxicity, and fate in the environment, September 2020.

three hundred million vehicles in operation presently, worth, it would appear, 450 billion water bottles and straws in terms of plastic pollution removal potential.[73]

Carbon (and Plastic) Capturing Pavements

Pavement Technology, Inc. has over forty years of experience in the pavement preservation industry, serving America's largest public works agencies and transportation administrators. At the ***Earthx2019*** environmental symposium, PTI formally introduced our state-of-the-art mobile source pollution-reduction and solar reflective "photocatalytic pavement" solutions after years of both field and laboratory testing success.[74]

Agencies have utilized PTI's core technology – maltene replacement[75] for decades to extend asphalt pavement life through molecular revitalization. MRT has shown to extend pavement life by 50% or more, cutting both repaving budgets and asphalt manufacturing emissions by the same through materially stretching-out repaving cycles.

Our **PlusTi™** family of road preservation products build upon the MRT success by adding photocatalytic materials which promote certain decarbonization and other environmental benefits including direct pollutant removal, cooler pavements, and better pavement hydrophilicity in addition to pavement preservation.

PlusTi™ "smog-eating" road products now have over five years of field performance testing. Select customers include Cincinnati, Akron, Orlando, Orlando International Airport, Raleigh, Charlotte, Durham, Charleston, and Austin. They have been tested by the **Florida Department of Transportation (FDOT)** and approved for USGBC LEED and ISI ENV accreditation. **PlusTi™** photocatalytic technology (PCT) is supported by U.S. and Canadian patents.

Designed to be an economical, yet robust "retrofit" technology for existing transportation infrastructure, **PlusTi™** products have proven to materially reduce vehicular emissions and mitigate the effects of heat islands. We believe agencies can immediately advance for scale their long-term goals to reach net zero carbon emissions with photocatalytic pavement upgrades.

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[73] FHWA and EPA.

[74] Zollinger DG and Joshaghani A, *Laboratory Investigation of the Effect of TiO2 Topical Treatments on Concrete and Asphalt Samples*, Texas A&M Transportation Institute, September 2018.

[75] GotMaltenes?: www.pavetechinc.com/got-maltenes/.

As a highly efficient photocatalyst material, titanium dioxide (TiO_2)[76] is a multifaceted photo-responsive mineral[77] rapidly gaining increased scientific and commercial interest for near-roadway microenvironments (ME) as it advances a host of preservation and environmental benefits, including:

- **Depolluting** near-pavement air cleaning applications, where TiO_2 reacted surfaces are able to oxidize a variety of pollutants and contaminants such as those emitted by vehicles, especially NOx, CO_2, MPP and VOCs, reducing ozone pollution and mitigating acid rain formation.
- **"Cool Pavement"** applications where TiO_2 enhanced pavements provide a solar-reflective top boundary, which lessens pavement related radiative forcing (RF) by reducing pavement heat absorption and averting the convective re-release of solar radiation that leads to the undesired UHI impacts. Significantly lower absorption also extends the life-cycle assessment (LCA) of pavements by slowing-down oxidation.[78]
- **Super-Hydrophilic /Hydrophobic** surfaces, which provide a rapid water-desorbing (faster H_2O *sliding*) pavement surface, are self-cleaning to remove contaminants (e.g., mold) and staining (de-soiling); protects against water intrusion to extend pavement life; and are rain displacing / ice-build inhibiting for inclement weather-related safety improvements for roadways.[79]
- **Water Purification** - photocatalytic surfaces also are stormwater purifying as the combination of cooler pavements with depolluting properties are antibacterial, antiviral, and anti-plastic.
- **Microplastic Decomposition** is 98% efficient with TiO_2.[80] Dangerous airborne and aquatic plastic pollution deposition into our environment estimated to be 85% sourced from roadway tire wear ($RAMP_{TWP}$), brake-pad wear ($RAMP_{BPW}$), and polymer modified asphalt ($RAMP_{PMA}$) degradation.

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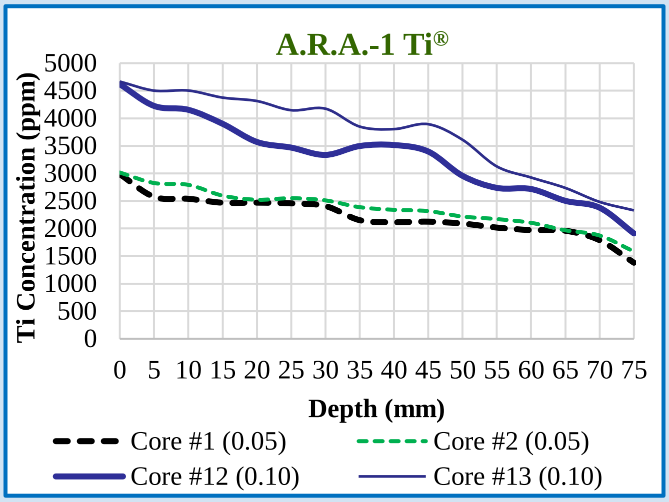
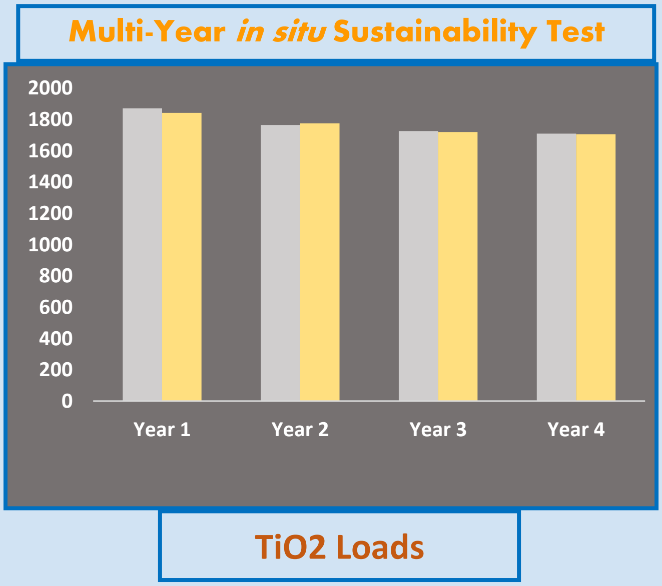
[76] Certain anatase type nanoparticle (<1 micron) TiO_2 naturally attracts, refracts, and deflects solar radiation efficiently, promoting redox reactions and solar reflectivity.
[77] *Polymers, Light and the Science of TiO2*, DuPont™ Ti-Pure® Titanium Dioxide, DowDuPont, www.dow-dupont.com.
[78] Gopalakrishnan K, et al., *Climate Change, Energy, Sustainability, and Pavements*, Springer, 2014.
[79] Arainpour F and Farzaneh M, On Hydrophobic and Icephobic Properties of TiO2-Doped Silicon Rubber Coatings, Department of Applied Sciences, Universite du Quebec, *International Journal of Theoretical and Applied Nanotechnology*, 2012.
[80] Nabi I and Bacha A, et al., Complete Photocatalytic Mineralization of Microplastic on TiO2 Nanoparticle Film, iScience, July 24, 2020.

Principal Testing Results:

Titanium Dioxide (TiO_2) Penetration and Load: Treated pavements are consistently indicating strong photocatalytic grade TiO_2 delivery and sustainability through and below wearing-course depth.

Figures 11 | 12 – PlusTi™ TiO_2 Penetration & Loading – Orlando International | City of Orlando





Source: Texas A&M Transportation Institute (TTI)

Nitrogen Oxide (NOx) Removal: Pavements field retrofit with TiO_2 are consistently showing 50% vehicular emission removal.

Table 2 – PlusTi™ NO_x Reduction – Texas A&M Center for Infrastructure Renewal (CIR)

Compound	NO Reduction Efficiency (%)					
Application Rate	Control Sample	0.05 gsy	0.06 gsy	0.08 gsy	0.10 gsy	0.12 gsy
A.R.A.-1 Ti®	NEGL	53%	57%	61%	53%	48%
Ti-introCME™	NEGL	48%	52%	55%	58%	53%

Source: Texas A&M Transportation Institute (TTI)

Table 3 – PlusTi™ NO_x Reduction – Orlando International Airport and Charlotte County (FL)

Site	NO Reduction Efficiency (%)				
0.08 gsy > TiO_2	Control Sample	A.R.A.-1 Ti® Sample A	A.R.A.-1 Ti® Sample B	Litho1000Ti® Sample A	Litho1000Ti® Sample B
Orlando International	NEGL	45%	43%	53%	57%
Charlotte Co. (FL)	NEGL			42%	46%

Source: Texas A&M Transportation Institute (TTI)

Urban Heat Island Mitigation: Asphalt pavements treated are consistently showing a 400% improvement in Solar Reflective Index (SRI) and qualify for U.S. Green Building Council LEED V4 Heat Island Reduction (HIR) and ISI ENV.

Table 4 – PlusTi™ Solar Reflectance – Orlando International Airport

Compound / Substrate	Solar Reflectance Index Values (SRI)					
Application Rate (a)	Control Sample	Control Sample	0.10 gsy	0.10 gsy	0.08 gsy	0.08 gsy
A.R.A.-1 Ti® / Asphalt	9	8	40	39		
Litho1000 Ti® / Concrete	24	24			38	38

Source: Texas A&M Transportation Institute (TTI)

Hydrophilic/Hydrophobic Pavements: TiO_2 is naturally hydrophilic, so treated pavements are indicating better water desorption properties to create a more hydrophobic or quick drying pavement effect. Prevents water intrusion, ice build-up, and surface ponding to reduce inclement weather-related traffic accidents.

Table 5 – Water Contact Angle – FDOT OGFC Test Bartow (FL)

Site	Water Contact Angle°				
A.R.A.-1 Ti®	Control Sample	TiO2 1 Visible Light	TiO2 1 UV Light	TiO2 2 Visible Light	TiO2 2 UV Light
FDOT Test	81°	82°	51°	81°	50°

Source: Texas A&M Transportation Institute (TTI)

Retrofit Technology is Low Cost and Covers All Transportation Surfaces:

- Application of a maltene rejuvenator enhanced with photocatalytic grade TiO_2 to asphaltic concrete surface courses estimated as low as $15,000 per lane mile (LM) of road.
- Application of a maltene-based longitudinal joint stabilizer enhanced with photocatalytic grade TiO_2 to asphaltic concrete surface courses estimated as low as $6,500 per mile of longitudinal joint.
- Application of a cationic penetrant fortified with photocatalytic grade TiO_2 to asphaltic concrete or Portland cement concrete (PCC) surface courses estimated as low as $12,500 per LM of road.
- Application of a cationic penetrant fortified with photocatalytic grade TiO_2 to most transportation infrastructure PCC peripherals estimated as low as $0.45 per square foot.
- Application of a lithium silicate sealer/hardener enhanced with photocatalytic grade TiO_2 to PCC surface courses estimated as low as $25,000 per LM of road.

Standard Verification Testing Included in the Above Pricing and Performed by Texas A&M University:

- ✓ TiO_2 Penetration and Load: XRF (fluorescent X-ray) analysis
- ✓ NOx Removal: Japanese Industrial Standard (JIS) TR Z 0018 *Photocatalytic Materials – Air Purification Test Procedure*
- ✓ Solar Reflectivity: U.S. Green Building Council (USGBC), LEED V4 Heat Island Reduction (HIR) [81] via Solar Reflectance Index (SRI) - ASTM E1980 - 11 *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces*
- ✓ Hydrophilic Properties: ASTM D7334 - 08(2013) *Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement*
- ✓ Tire and Other Roadway Microplastic Debris Removal: ASTM E1252 – *Infrared Organic Spectrometry (FTIR)*

[81] Same for Institute for Sustainable Infrastructure (ISI) ENVISION, www.sustainableinfrastructure.org.

TiO2 Enhanced Roadway Zone of Influence

Engineers prefer the concept of a “zone of influence” when describing the impact(s) on or from a structure from multiple dimensions. In this sense, a photocatalytic pavement is a three-dimensional structure reacted through a catalyst material imbedded near the surface and by the power of the Sun from above.

A TiO_2-bearing roadway creates *in effect* a natural electrochemical energy field that spans about eighteen feet [82] in all directions from the roadway surface. This zone of influence acts like a tunnel of perpetually solar charged particles – *oxyradicals*[83] that surround vehicles traveling across the roadway as if they were passing through a photo-energized *pollution scrubbing subway*.

Figure 13 – Solar-Charged Particles Swarm Exhaust

Source: Pavement Technology, Inc.; W/In Marketing

[82] de Dios J, del Campo JM et al, *Decontamination through Photocatalytic TiO_2 Additions – Past, Present and Future*, International Conference on Emerging Trends in Engineering and Technology (ICETET), London 2014.

[83] Photocatalytic Reaction(s): superoxide and hydroxyl radicals (collectively - *oxygen radicals* or “oxyradicals”) are produced by a combination of light energy and oxygen in the presence of a catalyst, creating these powerful oxidants via accelerated redox with an efficient metallic semiconductor such as TiO_2.

As described, certain vehicularly introduced compounds, including hazardous air pollutants (HAPs) such as NOx and other ozone precursors as well as microplastic debris are "captured" (converted to harmless) before they can escape beyond the zone of influence.

Harmless NOx resultant is absorbed by ground vegetation and routine street sweeping adding no additions to the nitrogen cycle, while removing an 849x [84] airborne toxin (NO_2).

Figure 14 – PlusTi® Application: Florida Department of Transportation (FDOT)

Source: Pavement Technology, Inc. US 17 Near Bartow (FL) 11/6/2019

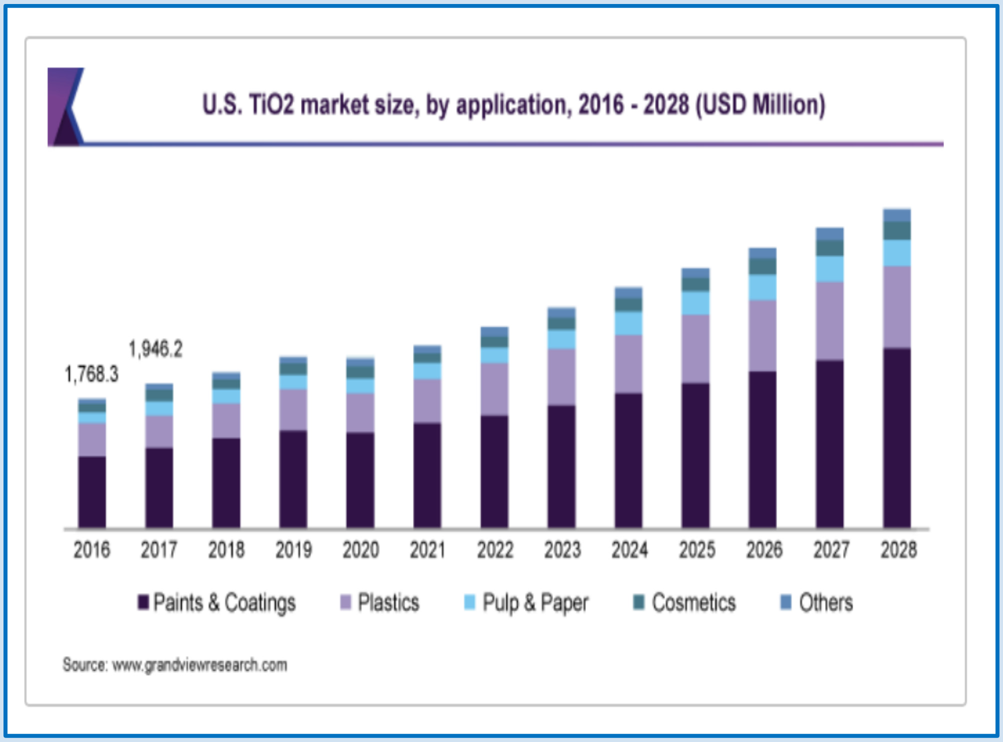
For most agencies, the bulk of their roadway inventory presents material greenhouse gas and microplastic point sources strategically ideal for a photocatalytic pavement upgrade to target emission reductions and to reduce the community's inherent heat island impact from critical roadway infrastructure.

[84] EPA: toxicity value of airborne nitrite gas to soluble forms of nitrogen.

TiO2 Supply, Cost & Environmental Burden

Known and estimated titanium reserves worldwide stand at 750 million and two billion metric tons, respectively.[85] Annual U.S. TiO_2 production tops two million tons or about 25% of global production.[86] Paints and coatings represent about 60% of titanium dioxide finished goods (Figure 13). The size of the global market is close to $20 billion annually and has been growing at a rate of more than 8% in recent years. The post pandemic supply chain is tight like all commodities, but the domestic market has been relatively stable.

Figure 15 – Domestic TiO2 Market



Source: Grandview Research, www.grandviewresearch.com.

The questions remain – what would wide use of photocatalytic materials in road construction mean in terms of TiO_2 market impact and paving costs?

[85] 360 Research Reports.
[86] Grand View Research.

Using a penetrant-based, spray-applied (retrofit) approach, we estimate no impact to the commodity market and little added expense to current paving and pavement preservation budgets.

Assume the U.S. market is comprised of four million lane miles of eligible pavement, and one wished to upgrade the system to photocatalytic over a ten-year deployment. The 400,000 yearly lane mile upgrade would consume 3.5 million pounds or about 1,800 tons of TiO_2.[87] That would equate to only 0.09% of U.S. annual production and 0.02% of global production. A retrofitted photocatalytic pavement consumes so little titanium because the technique targets the upper six (6) millimeters of pavement for TiO_2 concentrations. Certain nano TiO_2 blends of anatase and rutile form are so highly photo-responsive that peak photocatalytic efficiencies are achieved at as low as 2,000 parts per million (0.2% of the wearing-course of the pavement).

Since the process of imbedding a small, targeted amount of TiO_2 into pavements "piggy-backs" already existing pavement maintenance and preservation techniques, the cost of the upgrade is only fractionally more expensive than routine maintenance. For new asphalt overlays, the added cost would be well under 10%.

In terms of environmental burden shifting, there is no environmental hazard related to the aqueous suspension of titanium dioxide[88] then sequestered into a pavement subsurface. TiO_2 itself is inert and non-toxic. And the small amount of TiO_2 required per lane mile of a retrofit photocatalytic pavement has a *feed-to-gate* CO2e of just 0.003 tons.[89]

Contrastingly, there is substantial environmental relief from deploying TiO_2 in roadway microenvironments:

[87] BlackwallPartners LLC.

[88] International Agency for Research on Cancer (IARC); California Office of Environmental Health Hazard Assessment (OEHHA), Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65).

[89] Ruszakla MJA, et al, Low Carbon Footprint TiO2 Substitutes in Paint, *International Journal of Chemical Engineering and Applications*, October 2015, University of Utah, Materials Science & Engineering Department.

Carbon Reduction Calculations:
Pathway to Negative Carbon Roadway Systems

In addition to PTI's *MRT life-cycle calculator* which includes a 50% or more capex savings and a 500 to 1 carbon savings over overlays and rebuilds,[90] PTI has developed a carbon capture model for our photocatalytic pavement solutions, in part, through the help of the Center for Infrastructure Renewal at **Texas A&M University**, the **National Center for Pavement Preservation at Michigan State University** and scientists from **DowDuPont**, **Alcoa**[91] et al.

A single mile of TiO_2 enhanced pavement is "valued" at the same carbon reduction capacity of a 15-acre forest[92] and can offset the annual pollution of more than 375 automobiles[93] or 4,500 tons of carbon equivalents annually.[94] Applying current market rates for carbon, which are half of the low-end Paris Agreement 2030 necessary pricing estimates, a mile of PlusTi™ enhanced roadway has a ten-year CO_2e NPV of over $275,000 which is eight-times the current estimated capital cost of the upgrade. In direct financial cost, a unit of carbon removed via a photocatalytic pavement cost about $1 in comparison to other carbon dioxide removal (CDR) technologies estimated to cost as much as $200 to $500 or more per unit of carbon removed.

Photocatalytic pavements are productive at removing carbon equivalents because one of the primary mobile-sourced pollutants – reactive nitrogen(s) are 298x the global warming potential (GWP) of a unit of CO_2. So, roadway MEs are a critical and advantaged target (point source) for carbon negative strategies.

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[90] Chehovits J and Galehouse L, *Energy Usage and Greenhouse Gas Emissions of Pavement Preservation Processes for Asphalt Pavements, Transportation Research Board*, 2010.

[91] Chemours (DuPont) Ti-Pure paint coatings; Alcoa Architectural Coatings – TiO_2 enhanced EcoClean Aluminum Panels.

[92] Nowak D, U.S. Forestry Service: *Air Pollution Removal Capacity of Urban Forests*.

[93] 25,000 AADT or "high volume" traffic road.

[94] EPA: Average automobile annual CO2e (CO2 + NOx); Texas A&M Transportation Institute PlusTi™ analysis.

Table 6 – PlusTi™ Multi-Level Environmental Benefits

	NOx	UHI	RAMP	MRT	WCA
Air Quality	X	X	X		
Energy Use		X			
GHG Emissions	X	X		X	
Human Health	X	X	X		X
Quality of Life	X	X	X		
Road Safety				X	X
Water Quality		X	X		X
Road LCA		X		X	X
Acid Rain	X				

NOx (Nitrogen Oxides); UHI (Urban Heat Island effect); RAMP (Road-associated Microplastics); MRT (Maltene Replacement Technology). WCA (Water Contact Angle / Hydrophilicity)

Elegant "Free Energy" Technology

TiO_2 photocatalysis is a 100% solar energy mechanism which efficiently scatters light energy that slows-down oxidative damage to organic compounds such as paints, coatings, and asphalts, making them much more resilient. In the case of an asphalt rejuvenator, maltene replacement restores the asphalt binder constituent lost to oxidation to "rejuvenate" it and the TiO_2 protects the pavement from future oxidation. A nifty combination of two proven preservation technologies.

The *cool* and *smog-eating* properties are environmental ground-breaking benefits to the nano chemically more resilient pavement. Air quality and heat benefits quite useful in our ever-extending built world. Both technologies are all natural (forged by Mother Nature) and create no environmental burden shifting. A single electric vehicle requires 25 pounds of lithium, but each photocatalytic lane mile can remove the emissions from >450 cars with only 9 pounds of TiO_2.

Figure 16 – PlusTi™ Carbon Removal

Carbon Emission Calculation - 1Mt (annual)

Musk Foundation XPRIZE Carbon Capture Technology Challenge

PlusTi™ Smog Eating Roads — A Better Way to Get There

1 million / 4,500 tons GHG removal per CLM per year = 225 CLM

Material/Pollutant	Measurment	Amount	CO_2e (tons)
Embodied Carbon: Manufacturing & Application:			
TiO_2	Pounds	8,100	(0.68)
Rejuvenator	Gallons	189,000	(4.5)
Asphalt Saves	Tons	1,452	1,665,000
Net			1,664,995
On Road Emissions (10yr):			
NOx, CO_2, VOC			10,120,000
Gross			11,784,995

Project Cost	225 CLM	$8 - $10 mil
GHG Removal	Tons	11,784,995
	Per Unit	<$1
Paris Value	$50-$100	>$600 mil

Source: BlackwallPartners LLC

Air Pollution Capture

Non-factory CO_2e makes up a quarter of all exhaust gases but just 0.5% of air.[95] So, there remains the problem(s) of paying for and scaling many of the "popular" technologies for directly capturing air pollution as they are invariably inefficient. Traditional direct air capture (DAC) employs use of large-scale carbon removal machinery, which require enormous energy to gather-up the same amount of greenhouse gas they emit. Despite billions of dollars invested, all have failed heretofore to even reach net zero let alone negative carbon.

[95] United Nations IPCC.

By comparison, grabbing carbon from factory smokestacks is a proven technology and costs about $60 per ton. Even if DAC strategies can resolve for their net emission problems someday with cleaner energy sourcing, they still will cost fifteen times [96] this even by the most aggressive estimates for improved efficiencies.

Aside from prohibitive financial hurdles, there are three stages of critical environmental issues unresolved – **capture**, **conversion**, and **storage** plaguing prevailing DAC technologies. Both capture and conversion require immense amounts of energy as stated and most storage strategies require ecologically questionable "dumping" of toxic carbon resultant (coal) into our soil, deep underground, or into our oceans.

PlusTi™ solves for all of the aforementioned. First, photocatalytic pavements require no machinery for capture hence no energy consumption. The CO_2e is transported right to the site in the form of an endless supply of vehicles. And since they are existing roads, no new or additional land use is necessary either. Second, conversion is 100% "free energy" because TiO_2 is a natural catalyst which creates tens of millions of "micromotors" per square meter using sunlight and a little ambient humidity. Third, the resultant (natural plant food) is consumed by near road vegetation in most cases or by routine street sweeping and existing water filtration systems where no vegetation exists, requiring no land or ocean "fills."

This is why the cost of pollution removal with road level photocatalysis is a fraction of the cost of machine-centric technologies, is highly scalable, and has no ecological or environmental burden shifting whatsoever. Photocatalysis merely intervenes in the carbon, nitrogen, or plastic cycles by avoiding the toxic airborne and water-born component of the cycle with no net additions. The truncated process is hence better than perfectly circular.

[96] BusinessWeek +Green: *The Delay in cutting emissions is opening up opportunities for technologies that promise to undo climate change*, May 2022.

Value Proposition

PlusTi^{TM} photocatalytic pavement solutions offer a host of roadway preservation and environmental benefits for an attractive "turnkey" price. PTI is a vertically integrated product developer, producer, and applicator along with our emulsion manufacturing arm – **D&D Emulsions, Inc.**

D&D has built a state-of-the art TiO_2 mixing plant, which is the only known facility designed specifically to combine select asphalt and concrete preservation compounds with photo-responsive minerals to precise performance specifications.

In single applications, PlusTi^{TM} products deploy at a rate of as much as 50,000 sq/yds per day (six or seven lane miles) by one crew outfitted with PTI's advanced equipment. In most cases, traffic can resume within twenty to thirty minutes or sooner with minimal traffic control.

For existing pavements, overlays, or new build, the solutions are very cost efficient and contemporaneously target pavement lifecycle extension, reduce vehicular pollution and tire-wear debris, produce a low emissivity surface course, purify storm water, and improve roadway safety.

For more information, visit *smog-eating road*.

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