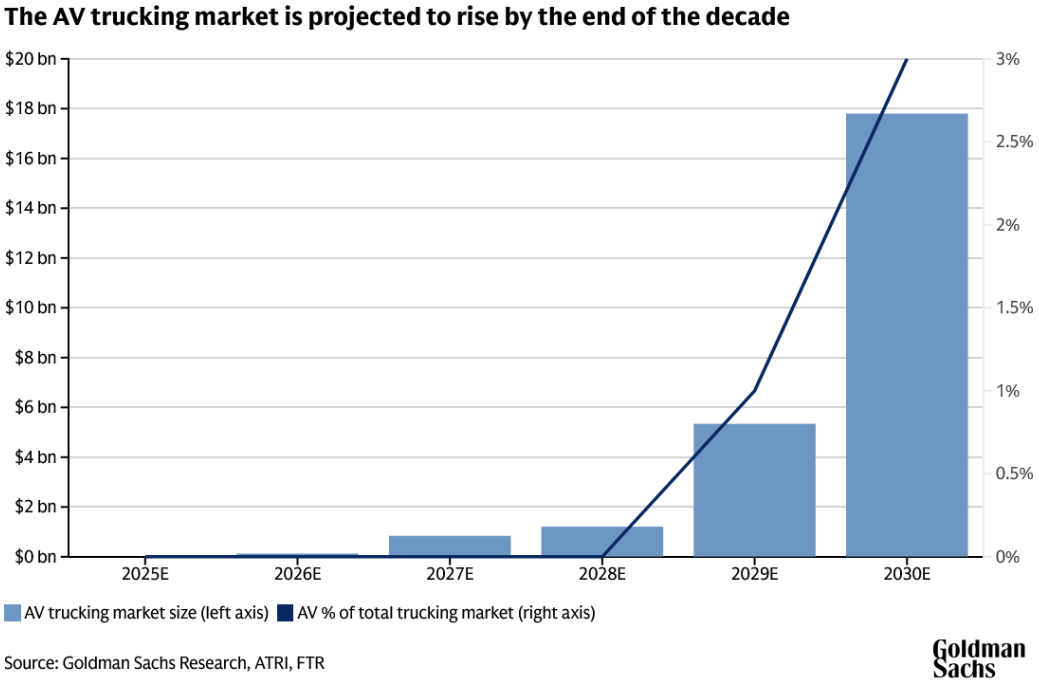
The Need For Infrastructure Improvements To Help Close The Nighttime Weather Safety Edge Case For Autonomous Vehicles

Introduction

Autonomous vehicle (AV) activity in the U.S. is hitting an important inflection point. On the passenger side, commercial availability of robotaxi services is expanding. 1,500 Robotaxis were on the road as of June 2025. These vehicles operate on an expanding number of route miles. By 2030, Goldman Sachs projects the number of passenger AV's to rise to 35,000, capturing 8% of the rideshare market. Meanwhile autonomous freight trucks (ATs) are being pilot tested by multiple companies. As of November 2025, they are servicing mid to long haul fixed routes in Texas and Arizona. ATs are also hauling frac sand in the Permian Basin. Goldman Sachs forecasts 25,000 ATs on the road by 2030.



To achieve both growth scenarios, some remaining safety challenges need to be overcome. Closing the nighttime inclement weather safety edge case is particularly difficult. Problematic, curvy sections of higher speed roadway, often with satellite and cellular signal interference, should be concerning to even the most ambitious members of the safety systems team.

The vehicle centric approach to solving this problem is simply insufficient. Upgrades to roadway infrastructure are critical if widespread, safe SAE J3016 Level 4-5 autonomous driving is to be

achieved. On-vehicle sensor and software technologies need redundant safety capability provided by new interactive infrastructure. The Brightpave Lane Marker offers one such solution.

State of Practice

Current Approaches

Current L-4 autonomous vehicles are operating on public roadways in two distinct modalities, passenger vehicles and larger trucks. ATs are conducting significant pilot tests on long stretches of open highway. Safety becomes an even bigger concern with 80,000 pound vehicles generating enormous destructive forces in a crash.

Fully equipped AVs utilize on-vehicle cameras, radar, and LiDAR to detect lane positioning and the operating domain. GPS, high definition dynamic maps and other proprietary software technologies supplement these safety systems to determine geographical location.

During nighttime driving, on-vehicle sensors rely on retroreflective road markings for validating lane positioning. Optics technology has not changed much in 30 years and includes glass spheres embedded in painted or thermoplastic binder material, thermoplastic microprismatic raised pavement markers (RPMs), and wet reflective tapes. Unfortunately, most surface applied markings experience retroreflectivity impairment when the road is wet, and all commercially available lane markings suffer from rapid degradation of their optics. The autonomous vehicle industry's reliance on these inadequate, "ubiquitous" pavement markings creates unacceptable risks to the general public.

One academic study analyzed the retroreflective degradation of 17 RPMs over time.[1] While conducted 30 years ago, very little innovation has occurred. None of the available markers studied maintained >10% of the retroreflective SI (specific intensity) after 24 months compared to their installed SI value. Importantly, only ~41% of the products were above 10% SI at 12 months and ~12% functioned at that level at the 18 month interval. Repair and maintenance cycles are mismatched to this known problem.

SI compared to SI at install	At Install	6 weeks	32 weeks	12 months	18 months	24 months
Marker count above 10% of original SI	17	17	6	7	2	0
Marker % above 10% of original SI	100.0%	100.0%	35.3%	41.2%	11.8%	0.0%

Summarized from study table

LED technology has been proven to overcome these retroreflectivity and degradation challenges. They are visible in standing water and maintain their luminous intensity over long periods of time.

[1] *Ullman, Gerald L. "Retroreflective Raised Pavement Markers: A Two-Year Field Evaluation In Texas." Texas Transportation Institute, Research Report 1946-3F (October 1994)*

Unfortunately, hard wired and first generation solar LED markers are not widely adopted due to difficult and lengthy installation time, significant power requirements, and other identified problems.
In addition to the noted limitations of machine vision “seeing” degraded optical markings, on-vehicle safety technologies face additional challenges. As an example, thermal sensors can be effective at identifying black ice conditions, but averaging $900 per sensor they are not cost competitive with simpler in-road temperature sensors. Utah’s "Connect the West” program is demonstrating the use of thermal cameras in roadside deployments, but they indicated this solution is too expensive to consider deploying on anything beyond high traffic count highways.

Emerging Approaches:

Advanced V2I (vehicle to infrastructure) RF solutions include the SAE J2735 V2X Communications Message Set Dictionary. This provides a standardized communication language for connected vehicles. One key part of the Dictionary is the MAP message which defines the physical geometry of lanes. Communicating lane geometry is crucial for autonomous truck safety on variably curved roadways, yet application of this messaging is currently focused on urban intersections. Without shifting these messaging resources to address the full autonomous trucking routes, redundant highway safety will suffer.

On a broader level, roadway fatalities are still occurring at epidemic incidence rates. Compared to 2014, 2023 motor-vehicle related fatalities increased by 26% to over 40,000, while the per traveled mile death rate increased by 18%.[2] Recent modest reductions in fatalities have been achieved, but the numbers are stubbornly persistent in spite of $24.5 Billion of safety spend allocated in the current 5 year federal budget cycle.[3] Autonomous freight now layers an additional set of fatality risks onto the overall safety problem due to their increased size. These risks need to be proactively addressed to avoid catastrophic accidents and public backlash as autonomous activity increases.

To achieve safer autonomy, better collaboration between industry and public roadway operators is required to deliver high Benefit:Cost Ratio infrastructure safety advances that align with the realities of limited budgets at state DOTs.

Opportunity

A durable, dual functionality lane marker is a game changer. Combining superior LED optics for traditional, assisted, and autonomous driving with enhanced V2X communication in a single device overcomes the budget challenges and risks of installing/maintaining separate systems. With proven LED safety outcomes, roadway operators can tap existing safety programs like HSIP grants that

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[2] National Safety Council, Injury Facts, Motor Vehicle Crashes, https://injuryfacts.nsc.org/motor-vehicle/overview/introduction/

[3] US Department of Transportation, Infrastructure Investment and Jobs Act Grant Programs, https://www.transportation.gov/infrastructure-investment-and-jobs-act/infrastructure-investment-and-jobs-act-grant-programs

unproven RF only solutions can't. Additionally, the connected autonomous vehicle use case is perceived as too small by DOT leadership to address when dollars are scarce.

Enabling Technologies

Brightpave Markers has engineered a highly effective, proprietary lensing solution. These lenses concentrate emitted light into a low angle vision cone, preventing light pollution and conserving power budget.

The markers have been designed with excess logic and general system capacity for adding low powered RF capability. At the regulatory level, allocated C-V2X spectrum resource is currently underutilized. With this available bandwidth, the ability to expand beyond intersection safety to widespread lane delineation can be addressed in the near term.

Expected Performance / Impact

LED technology already has a proven, correlated 50% reduction in injury accidents. In a 4 mile Colorado highway test conducted by CDOT, Brightpave Markers research staff projected a BCR of 43.6 based on a 5 year discounted benefit of $9.9 Million and preliminary cost estimate of $227,500.[4] Longer lived, snowplowable LED markers should drive comparable accident reduction for Advanced Driver Assistance Systems (ADAS) and AV systems.

With a 10 year targeted life meeting MUTCD retroreflective equivalent standards, LED markers provide longer safety benefits versus short-lived wet retroreflective solutions. As autonomous vehicles increase their numbers on the road, ensuring inclement weather visibility of pavement markings for onboard cameras is crucial for avoiding an increase in lane departure accidents.

As previously noted, autonomous "big rigs" have a much higher mass than passenger vehicles resulting in more severe accidents. Preventing autonomous truck lane departure accidents should result in fewer associated fatalities reported under the KABCO injury classification scale.[5] Reducing fatalities is the core of the Vision Zero program adopted by the U.S. DOT. But reducing the human tragedy and societal costs of serious injuries is an additional safety goal.

Remaining Challenges

As an emerging technology solution, a number of open questions and risks need to be addressed to bring RF lane delineation to reality.

Most important is overcoming latency to complete the validating RF signal handshake with a passing vehicle at highway speeds. Security certificates are exchanged before any further communication can occur. This becomes even more difficult if the marker is not always on and requires a "wake up" message to begin the process. A properly conceived mesh network may be one solution that could

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[4] Brightpave Markers, Analysis of 2014 CDOT crash analysis and BCR of new LED marker (2025), https://brightpavemarkers.com/CDOT-BCR-analysis

[5] American National Standard Institute. "Manual on Classification of Motor Vehicle Traffic Crashes." ANSI D.16-2017, Section 3.1.2

overcome this challenge. That is one area of focus for further industry development.

Having an ample power budget for an “always on” RF device combined with nighttime LED lane delineation becomes challenging as batteries degrade over time. While battery technology continues to improve, oversizing the initial storage capacity is required to overcome degradation, particularly with extreme heat and cold charging conditions.

And finally, staying current on evolving connected vehicle technology standards is critical. Since the mid 2000’s a number of concepts and spectrum allocations have come and gone. DSRC was abandoned for C-V2X and in 2018 the FCC reallocated parts of the 5.9 GHz spectrum to support the ecosystem. There are no guarantees that this allocation becomes permanent. Until vehicle OEM’s commit to deploying V2X capability in their vehicles, roadway operators are hesitant to spend scarce budget capacity where there is no demand.This adds to the threat of losing the spectrum allocation to other wireless needs.

Why Now is the Right Time

First generation LED approaches to lane marking suffer numerous other technical challenges not covered in this paper. With high upfront installed costs, industry has ignored further development of a perceived “niche” technology. Concurrently, any RF networked road IP has focused on piggybacking on the installed base of rapidly degrading retroreflectors. It misses the huge opportunity to combine RF with long-lived LED technology in an economically superior, truly integrated solution. This new RF/LED combination can deliver an abundance of roadway data that furthers the ability to save more lives.