Infrastructure Vision Whitepaper

Beyond Static Pavement: A Unique Traffic Solution

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Abstract
Flash forward. The year is 2050 in Los Angeles. Smart roads, bridges, and tunnels have not only become the standards of innovation, but also the pride of our nation. They interconnect cities and sprawl across towns with the flows of people, goods, and services. They resemble the cells, plasma, and nutrients traveling through biological systems. And, like evolution, our transportation infrastructure has also adapted to the rise of urbanization through a concept called the "Smart City". Urbanites now enjoy unencumbered rush hour commutes, safe pedestrian crossing, and a truly beloved transportation system. Drivers have seen average transit times halved in a span of two decades. Across the nation, roadway congestion that accounted for ~$100 billion a year has now reduced by 50%, fallen from its peak through the recovered time and productivity. The once ballooning traffic fatalities, about 33,000 fatalities a year, no longer drains the local economy another ~$100 billion a year on medical expenses and civil penalties. Through creativity and action, this utopian imagery can be forged in the future of our reality. Here a unique vision is introduced to bridge the gap of possibilities. Akin to constricting blood vessels for regulating flow, the approach outlines a plan to outfit roads with "muscles" that can enforce coordination between vehicles en masse. It would fill the gap, along with sensors and data, needed to make our transportation system adaptive to the changing needs of the 21st century.

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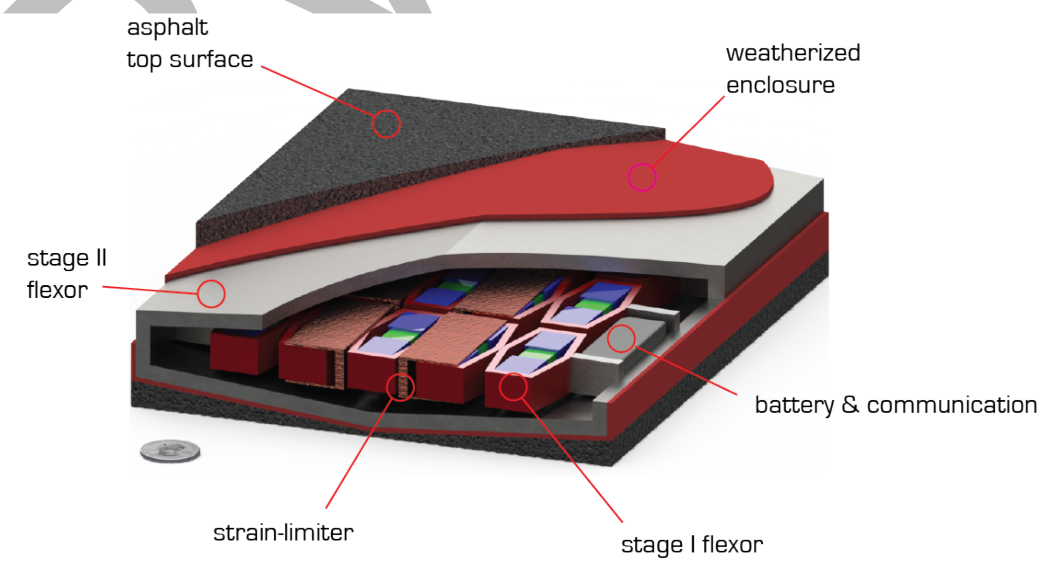
Executive Summary

A dynamic pavement system is being developed to create value for existing road stock. Instead of building new roads in the already-crowded cities, the unique approach leverages technology to build smart cities. The technology is a device that can extract energy from the weight of overpassing vehicles, while having the ability to dynamically alter the road profile as needed. By harvesting vehicle energy, the pavement device is fully self-sufficient. No maintenance would be necessary. In contrast, the dynamic profiling can deter speeding and enforce coordination. The approaching cars to a busy intersection or road constriction would be signaled to slowdown prior to the development of an expanding traffic jam.

At scale, smart roadways would benefit all drivers without the adoption delay accustomed to most other vehicle technologies (i.e., EVs and connected vehicles). The retrofit of existing roadways is also cheaper, faster and more effective than building new roads. Further, the renewable electricity generated can offset peak demand and, during blackouts, provide power for lighting and signaling. Altogether, the adoption of Adaptive Pavement can greatly improve convenience, safety and mobility, the three tenets of effective transportation. These and other various stakeholder benefits include:

- Public health benefit from reduced CO2 and NOx emissions
- Capital efficient solution with 10X performance and 1% cost of roadway expansion
- Accelerated timetable with retrofitting existing road stock during pavement resurfacing
- Lower operational cost with self-powered, maintenance-free operation
- Energy sustainability with energy regeneration accounting for <1% of rolling resistance
- Taxpayer appeal for having a equitable solution to infrastructure upgrades



Background

Congested roadways represent an opportunity to improve transportation and mobility. However, the cost of large construction projects makes quick, equitable progress difficult. The slow timetable is exacerbated by the need to balance spending on new, capital-intensive projects versus maintaining a broader proportion of existing stock.

One alternative approach is to leverage technology to mitigate these trade-offs and make existing roads more responsive, flexible and adaptable to real-time traffic fluctuations. Akin to blood vessels constricting to regulate flow, a network of pavement-embedded devices may be able to deter speeding and, at the same time, improve throughput and safety. The greatest benefit of infrastructure upgrades would be equitable to all drivers in larger (e.g., San Francisco) and mega (e.g., Los Angeles) cities.

The problem with roadway expansion goes beyond its astronomical cost, the gentrification of neighborhoods, and the non-equitable spending of public funds. *The simple fact is: Adding new lanes does not relieve traffic congestion.* In Los Angeles and the neighboring Orange County, for instance, measures as being passed to raise funding for roadway expansion projects.

Adaptive Pavement during on and off switching

The subject is a 13-mile stretch of the Interstate 405 linking Long Beach and Costa Mesa, which consistently ranks in the top 5 of worse traffic in the state, and possibly in the country. During rush hour, the outbound lanes from LA become congested as five lanes become four. The havoc predictably last 3 to 4 hours on end and wastes 67 years for motorist annually. In response, the solution on the horizon is a $1.7B project that aims to add 1 extra express lane to both sides of the I-405. That is $130 per mile of roadway.

At best, critics point out a conundrum: more drivers that otherwise don't drive during rush hour would fill in the extra supply of lanes and negate the intended benefits. Officials of surrounding areas also claim that they are being forced to subsidize the rest of the county's infrastructure upgrade.

If massive investments are made in improving traffic and mobility, then the return should be equally massive. Compare to roadway expansion, an ideal solution should provide:

- Greater safety
- Faster commute
- Lower cost
- More convenience
- Broad appeal and accessibility
- Shorter timetable
- Maintenance-free operation

Fortunately, new technologies do exist that can incorporate these benefits into the backbone of our national highway system – one of the greatest engineering feat of the 20th century. Rather than making it obsolete, new technology can bring life to an old system. Road-embedded smart devices can impart coordination to traffic. They can deter speeding to avert and/or alleviating traffic jams. The simplicity of the approach could improve our aging roadways and infrastructure at a fraction of the cost of new infrastructure.

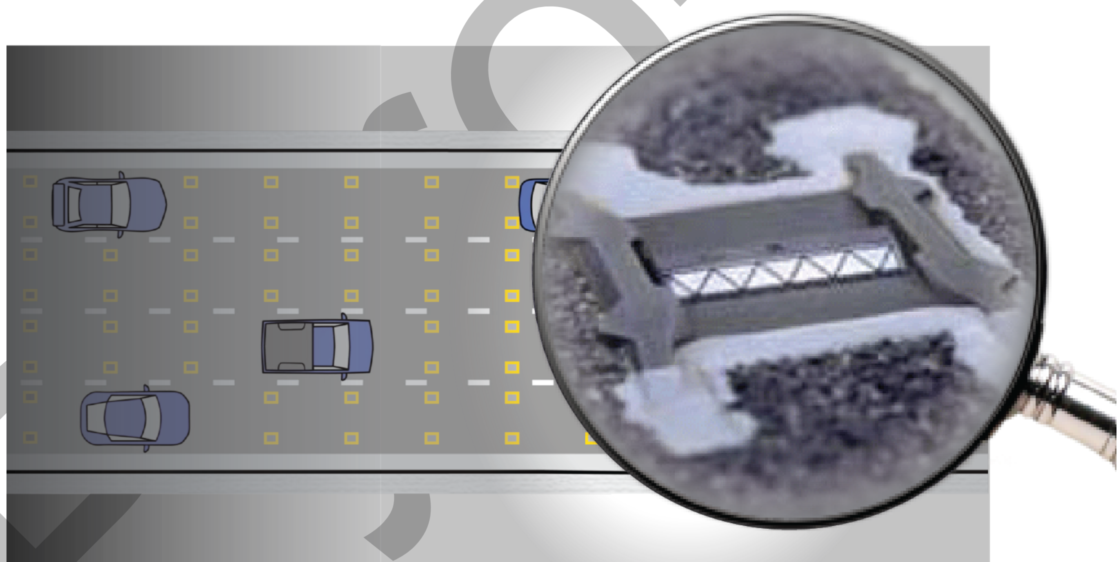


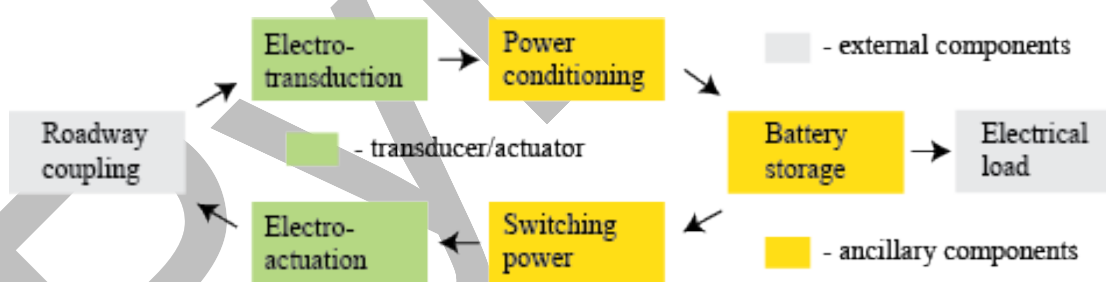
Illustration of the Adaptive Pavement System

Technology

Our patented Adaptive Pavement system is low-maintenance and can operate without external power. This is essential for the plurality of devices needed to make roads adaptable to traffic. Embedding a network of electrical wires would be impractical and prone to failure. This negates the effective lifetime of the pavement devices, which operating without moving parts is expected to last greater than 15 years – less robust electronic components can be mounted above ground for serviceability.

Specifications	
Device size (LxWxH)	6”x8”x2”
Device power	50 - 120 W
Device life	12 years
Maximum wheel force	20 kN
Maximum actuation	5 mm
Power per lane-mile	300 kWh/hr
Cost per lane-mile	$200K
Configuration	Pavement interlay

The Adaptive Pavement mechanism operates simultaneously through two primary modes: 1) Regenerative and 2) Reactive. In the regenerative mode, the self-sustaining power charges the on-board electronics by extracting the vibrational energy produced by the wheel contact. In the reactive mode, the devices can adjust to form either a flat or protruded pavement surface. Depending on the traffic condition, a flat surface allows unimpeded driving during free-flow traffic. During congestion, a protruded surface will deter speeding and coordinate all vehicles to slow down. Through each wheel contact, there is enough power generated regardless of vehicle type, speed and weight. At 1” height, the device can be installed during road resurfacing to reduce soft costs.



The dual-mode operation for the regenerative and Adaptive Pavement devices

<u>Power output</u>

Electricity is needed for force detection, data communication and pavement actuation. The key is to adapt the device to vehicles having different speeds and weights. The design should also have low latency so that it accommodates tighter spacings between vehicles. These conditions would occur during high throughputs in peak *free-flow* traffic. Also, tighter spacing is typical for small passengers cars given its nimbleness compared to long-haul trucks.

The anticipated power output at scale is 200-300 kWh/hr per km-lane during peak traffic (~2100 veh/hr). This is equivalent to ~6000 averaged homes serviceable by a 4-lane highway during rush hour.

Force-limited compression

One drawback of current devices is its inability to attain the rated performance for weaker compressions (i.e., humans, cars, trucks, etc.). To overcome this challenge, a force/strain limiter would be installed to restrict the wheel force of heavy vehicles, such as Class 8 trucks. This way, the harvester would generate the designed capacity from *both* cars and trucks.

Unobtrusive retrofit

The typical thickness of the asphalt layer is 3”-4”. That will limit the height of the device so that it can be installed without affecting the roadbed. The target device thickness would be 1” tall, which is enabled by the used of narrow (1-cm^2 cross-section) electro-stacks.

Efficient battery charging

Efficient charge transfer is invariably required since active cooling is not practical for roadway-embedded structures. Rectifying the excitational voltages into a low-ripple DC signal requires a novel switching convertor topology[1].

Data Analytics

Onboard algorithm acquires and diagnoses the electrical signal generated to build a holistic view of real-time traffic. Lane-specific data on traffic speed, density and throughput can be computed and transmitted to a common gateway for data-as-a-service (DaaS) mobile app development.

Wireless communication

Low-energy Bluetooth and gateway will be used for communication between devices and the central network. COTS electronic components will be used to meet Federal Communication, transportation safety[2], and smart city communication standards[3].

Multi-purposed Enclosure

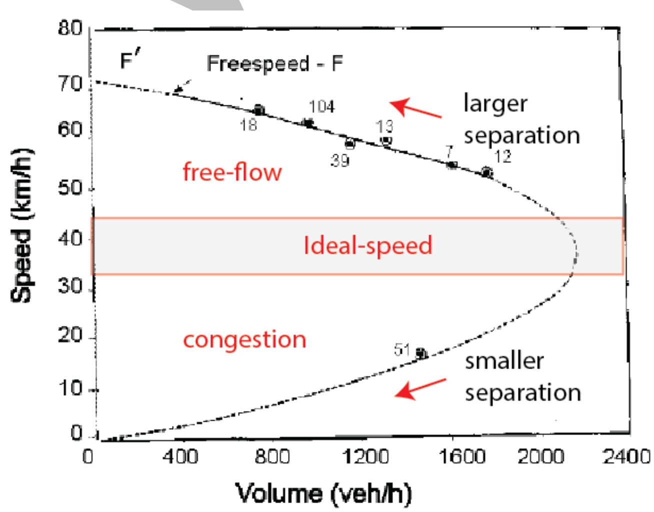
The interface between the device and pavement will provide:

- Abrasion resistance top surface that supports repetitive shear and compressive loading.
- Weatherized protection against debris and moisture.
- Direct thermal path to the outside environment for heat dissipation.

Design sketches of the Adaptive Pavement device.

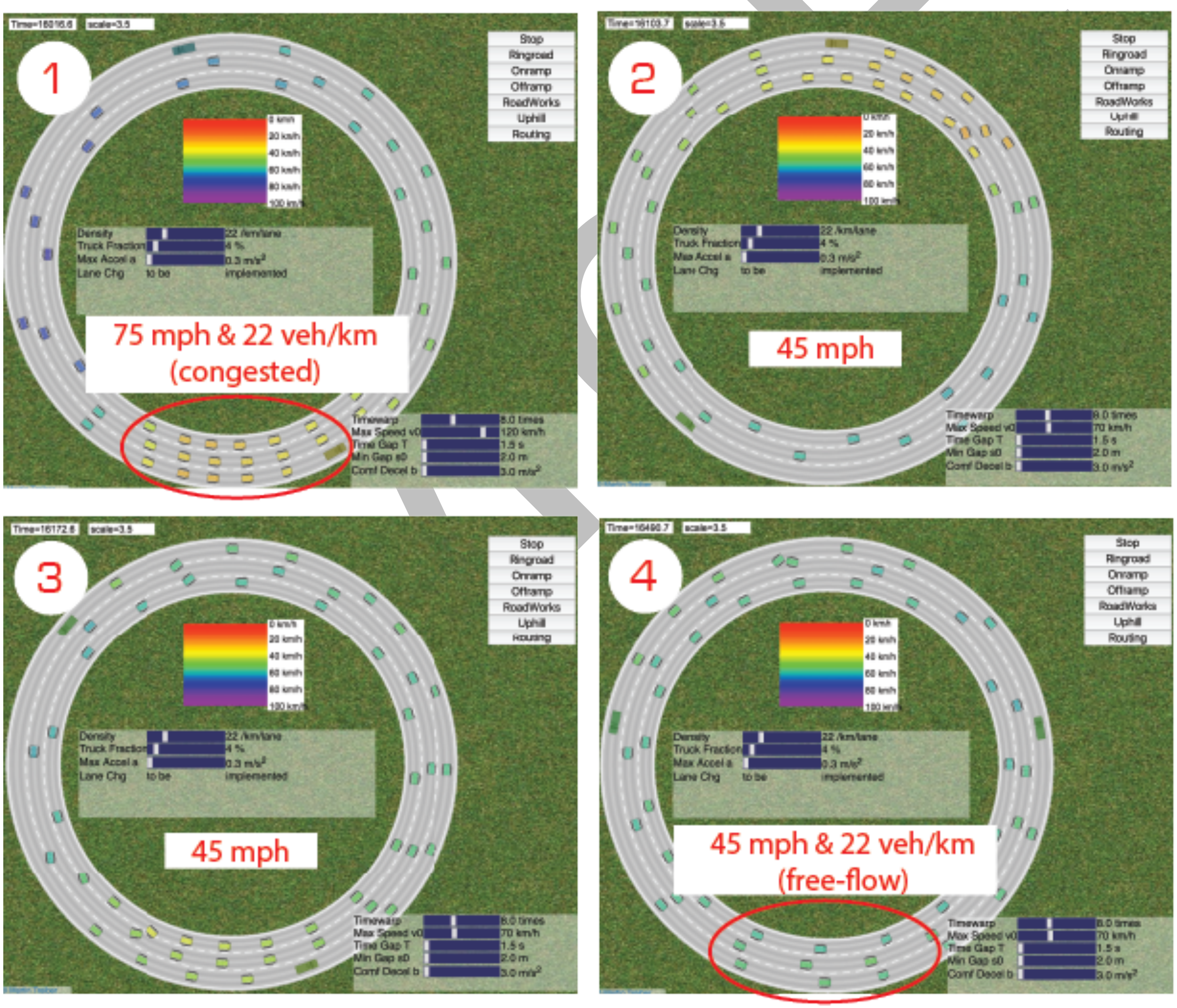
Key Challenges

The challenge is: How to use Adaptive Pavement to move 1000% more cars through our existing roads at 1% cost of roadway expansion? The key to overcoming traffic congestion is with coordination. Delayed breaking, for example, causes more of it and perpetuates the stop-and-go traffic upstream. The resulting average of the speed, then, equals the traveling wave speed of the incessant breaking, one after another. Quantitatively, this reduces the traffic flux, or *throughput capacity*, the most important metric that measure the total number of vehicles crossing an imaginary plane on a highway per a interval of time, i.e. veh/hr.



The Fundamental Traffic Diagram

To understand how limiting vehicle speeds can improve throughput, the key is to understand how a small bottleneck can propagate and build up into long stretches of stop-and-go traffic. Luckily, such transition between free and congested flows is highly predictable. It has been well documented through traffic data that there exist distinct relationships between vehicle speed and throughput. One is for free-flow and the other is for congested flow. The so-called “Fundamental Diagram for Traffic Flow” shows that the two relationships converge at an ideal condition where the highest throughput can be achieved (at approximately 2200 veh/h). The corresponding speeds are between 38-42 mph, which is slower than the speed limit of most U.S. freeways. By controlling vehicle speeds en masse within the said range of speeds, it would be possible to avert traffic jams and its propagation upstream.

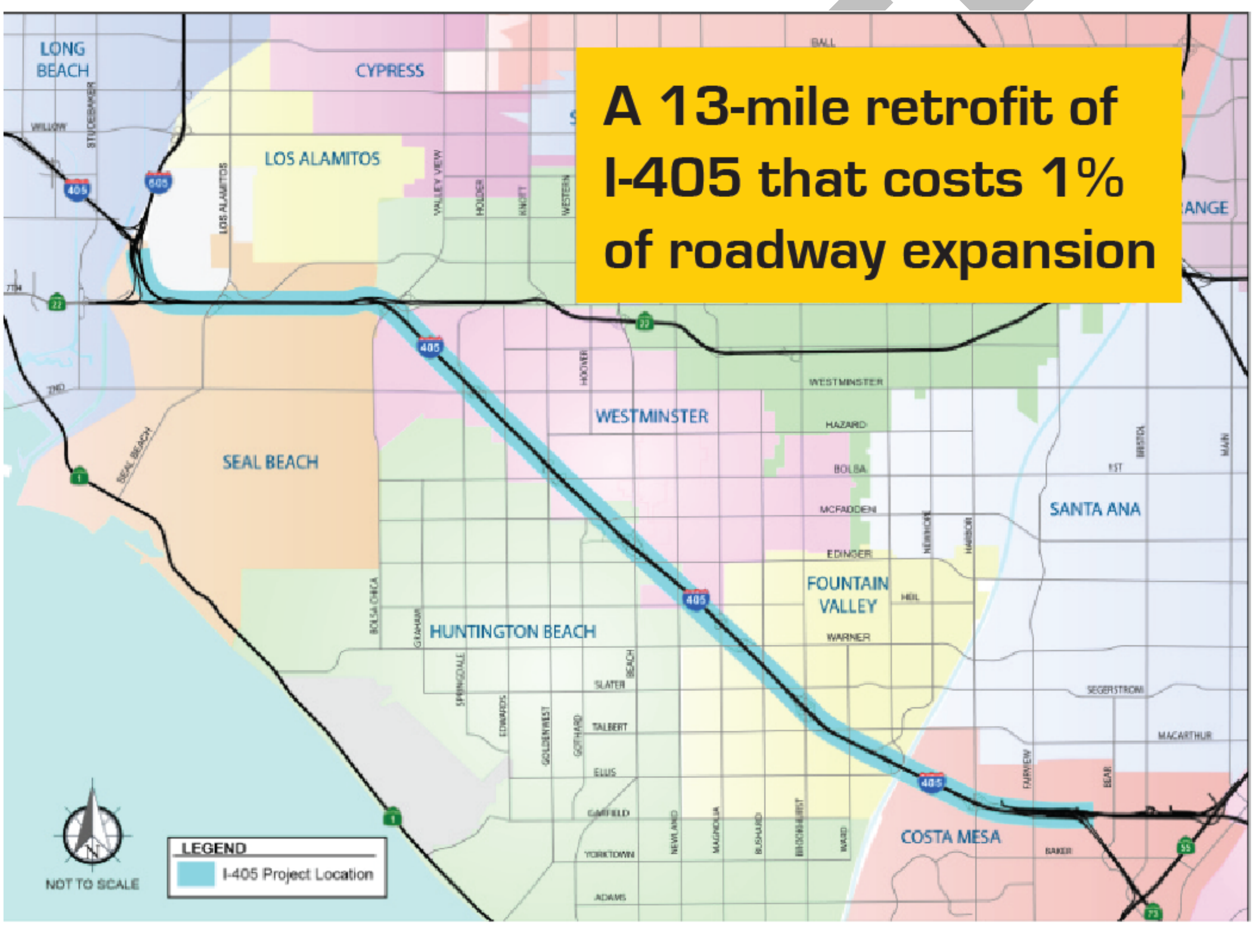


Time-sequenced closed-loop simulation of traffic flow

Mitigating Strategy

Typically, a traffic bottleneck occurs where there is a local decrease in road capacity and/or increase in vehicle density. Physically, this can be due to road constriction with reduced lanes or a sudden increase of cars from on-ramp locations. Here, the assumption is that, by softening the transition, i.e., by slowing the on-coming traffic, congestions can be diffused quickly or even averted entirely.

Traffic flow simulations make it possible to see the effect of reducing vehicle speeds en masse for alleviating congestion. The result (1 through 4) shows that congestion can be remediated by limiting the maximum vehicle speeds. Simply by reducing the limiting speed from 75 to 45 mph, the simulation shows that a well-defined bottleneck slowly diffuses and becomes free-flow traffic once more. From the snapshots, one can also observe that vehicle speeds become more uniform. The result is that the average lap time for the faster congested vehicles is 73 seconds, whereas it is 48 seconds for the slower free-flow scenario. That is a 30% reduction in travel time by adjusting the speed limit to maintain free flow.



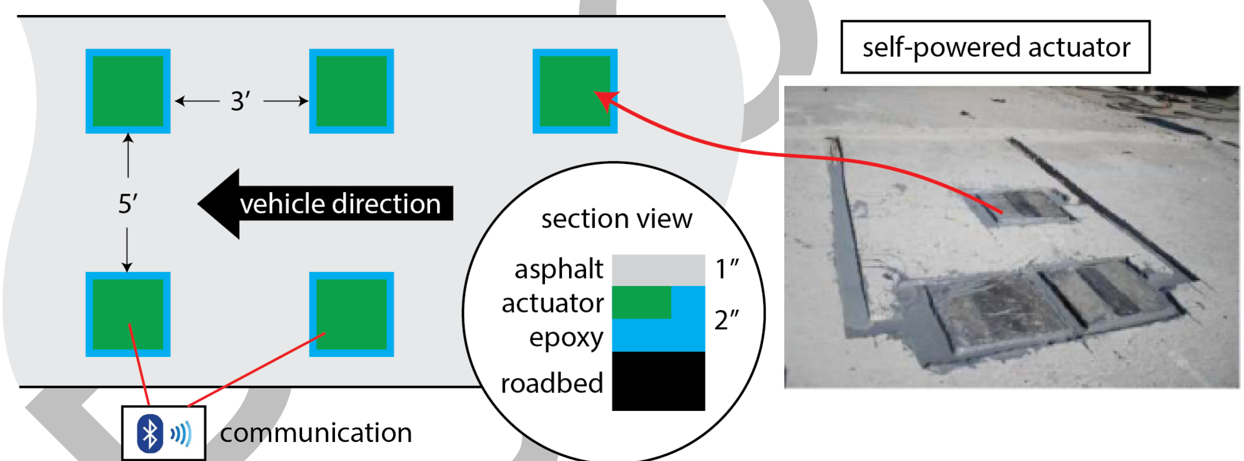
The 13-mile stretch of Interstate 405 in Los Angeles as candidate for retrofit.

However, this close-ended simulation (i.e., cars traveling in a circle) does not allow for the propagation of the bottleneck to fill the entire track. On open-ended roads, real traffic jams would expand upstream towards the oncoming traffic and greatly limit the overall throughput. Using the Fundamental Traffic Diagram, a free-flow traffic at 38-40 mph yields 2100 vehicles per hour, or ~10 times the capacity of a congested traffic with 200 veh/hr. Unfortunately, dense traffics fall into congestion much more readily than maintaining free-flow – it is an unstable condition due to the delay in driver reaction time. This equates to 800% faster commutes for the most problematic corridors such as the Interstate 405.

The solution to improving mobility lies within existing road stock. For the depicted 13-mile stretch of I-405, there is significant room for improvement beyond a simple static road. By throttling and delaying the upcoming traffic, the road can enforce coordination to avoid the transition into congestion.

For clarity, vehicle throttling would not cause on-ramp delays and create congestion onto local streets. Vehicles are throttled much further upstream a bottleneck location. It is the coordinated slowdown of nearly all vehicles across every lane that helps to remediate traffic.

For completeness, other relevant factors such as reaction time, vehicle acceleration and inter-spacing can be modeled but would be difficult to implement in practice. After all, these factors are also functions of the vehicle speed (e.g., faster speeds require longer spacing).



Demonstration of roadway-embedded smart devices

Technology Demonstration

An early demonstration of Adaptive Pavement has yielded excellent results at signaling drivers to slow down. The findings yielded that up to 5 mm of protrusion is needed to generate adequate disruption to limit vehicle speeds to 35 mph. For a 3 mm protrusion, drivers tend to maintain speeds between 40-50 mph. As a result, the Adaptive Pavement would be effective at limiting vehicle speeds and better utilize existing roadway infrastructure for meeting peak demand and density fluctuations. Those features that were either demonstrated or supported include:

- ‘Intelligent’ operation able to adapt form and function to traffic conditions in real-time

- Direct visual and haptic feedback to motorists for advance traffic warning
- Effective safety countermeasure for reducing vehicle speeds en masse
- Intelligent data analyzer for lane-specific information on vehicle type and speed
- Weatherized package against moisture/debris for maintenance-free operation

From the pavement retrofit, the project yielded a simple solution to installing Adaptive Pavement. As depicted in the figure, the first method lays the devices down during road repaving, following these steps:

1. Mill and remove road top surface.
2. Arrange the individual units onto the cement roadbed.
3. Place liners to form a 0.5" gap around the units.
4. Pave with base coat and asphalt, followed by rollers for smoothig.
5. Remove liners and fill the gap between device/asphalt with polyurethane epoxy.

The liner resembles a square frame that serves two main functions. One, the gap filled with a flexible epoxy material would allow device movement. Two, it prevents the heavy rollers from crushing the devices. The asphalt layer on top of the device can be either prefabricated during manufacturing or laid during paving.

	New Lanes	**Smart Lanes**
Cost per mile:	**$100M**	**$1M**
Project duration:	**4 years**	**3 months**
Capacity:	**1000 cars/hr**	**23,000 cars/hr**
Commute time:	**2.5 hours**	**18 minutes**

Cost comparison between roadway expansion and Adaptive Pavement retrofit for improving a 13-mile stretch of Interstate 405 linking Costa Mesa and Long Beach

1.1 Economics & Buildability

The economics of retrofitting roadways with Adaptive Pavement is extremely favorable compared to adding new roadways. It was found to be extremely cost effective as the devices were installed during road paving. No procedural change or additional installation costs were assessed since a portion of asphalt materials was obviated by the device footprint. The simple installations were enabled by the 1”-thick Adaptive Pavement, which is less than the typical asphalt layer of 3” - 4”.

Moreover, the concept is highly scalable for cities where the predominant mode of travel is driving. No new land is needed for construction or risky mobility concepts to be adopted. Only existing roadways are needed for retrofit by adding interconnectivity and intelligence to the aging infrastructure. Compared to the road widening of the I-405, the difference in cost is staggering. The new 4-year, $1.7B construction project will take 10-times longer than retrofitting roads with Adaptive Pavement devices. The latter can be done during asphalt resurfacing so that normally scheduled maintenance can be completed concurrently.

Dynamic signage powered by Adaptive Pavement for pedestrian and vehicle coordination

1.2 Coverage

Greater than 80% percent of traffic-related accidents occur during rush hour. This makes sense because roads and signage with outdated designs cannot cope with overcrowded intersections or heavy traffic. New research, for example, points to creating narrower lane and tighter curb radius for improving driver attentiveness and reducing turning speeds. “Road Dieting”, as it is called, helps urban centers with heavy foot traffic.

Despite the benefits of having permanent fixtures, further improvements can be made with dynamic countermeasures such as Adaptive Pavement. These areas include:

- Pedestrian crossings without traffic lights
- Highways that face high volume and high speed traffic
- Parking lots and shopping centers predominated by irregular walkways and roads

All of the above cases are absent of traffic lights and, as a result, are the most dangerous. At pedestrian crossings, for instance, safety can be much improved with a pavement that can signal drivers to slow down. Beyond sensing, Adaptive Pavement can dynamically alter the road surface to signal drivers as they approach an intersection. This would drastically reduce the chances for pedestrian injury when visibility is impaired by other vehicles or in bad weather.

Beyond city streets, dynamic countermeasures are applicable to freeways during both peak and off-peak traffic. Take highway congestion for an example. Adaptive Pavement would stay leveled to road surfaces when traffic volume is low. This accounts for most of the hours in a day when normal driving conditions are expected. During rush hour, in contrast, road surfaces would adapt to the increased volume and respond to deter speeding and alleviate traffic. Like before, such direct road feedback would not be adversely impacted by other vehicles or in bad weather.

The wide-ranging adaptability of Adaptive Pavement addresses scalability by its ability to integrate into different types of roads and accommodate various driving conditions.

1.3 Adaptability

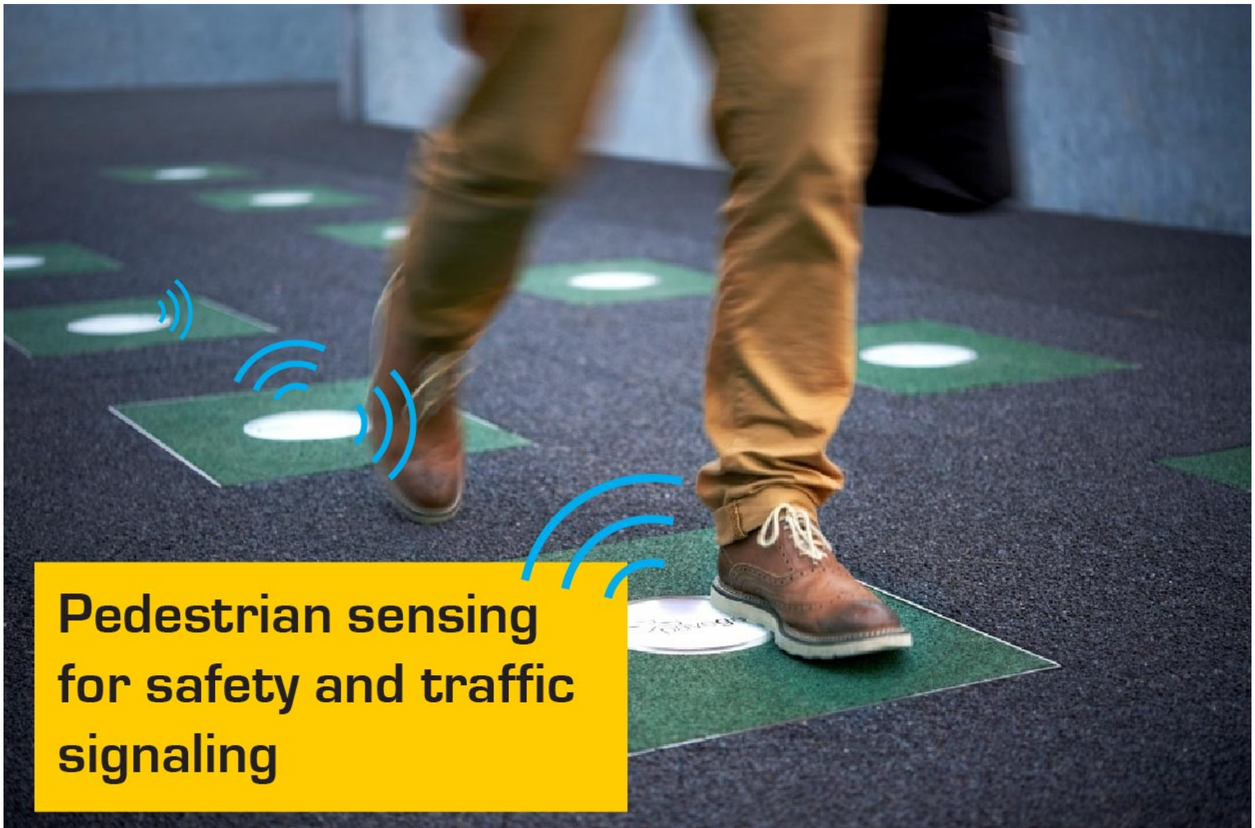
There are numerous ways that Adaptive Pavement can improve existing infrastructure. Sections below outline the possible applications ranging from city streets to urban outskirts dominated by highways.

<u>Pedestrian Safety</u>

In city streets, passive traffic management techniques such as road dieting – narrowing lanes to deter speeding – have shown proven results at improving pedestrian safety. By far, the leading factors are *speeding* and *distracted driving*. If both can be mitigated, then the total number and the severity of pedestrian injuries would fall dramatically. By 2050, cities can retrofit busy road intersections with Adaptive Pavement devices that physically signal drivers to slowdown when a pedestrian is detected at crossing.

Also, an Adaptive Pavement tile that flexes by 5mm when stepped on, results in up to 8 watts of kinetic energy. Enough tiles and enough footsteps can create enough energy to be stored in batteries, or to help power streetlights and other electrical items. Each tile also boasts a unique proprietary wireless communications technology that uses only 1% of its power to transmit data about the number of footfalls and energy generated. This means city officials and can see how many people are passing through each area. At an intersection, the tiles can signal upcoming traffic automatically for safe passing.

By averting just 10% of pedestrian deaths, a city such as Los Angeles can save $100M/yr (~330 deaths in 2014 at an average cost of ~$3M each). The total cost of retrofitting 817 of the most dangerous intersections that represent 35% of all incidents would be ~$100M.



Adaptive Pavement use for pedestrian detection and warning system

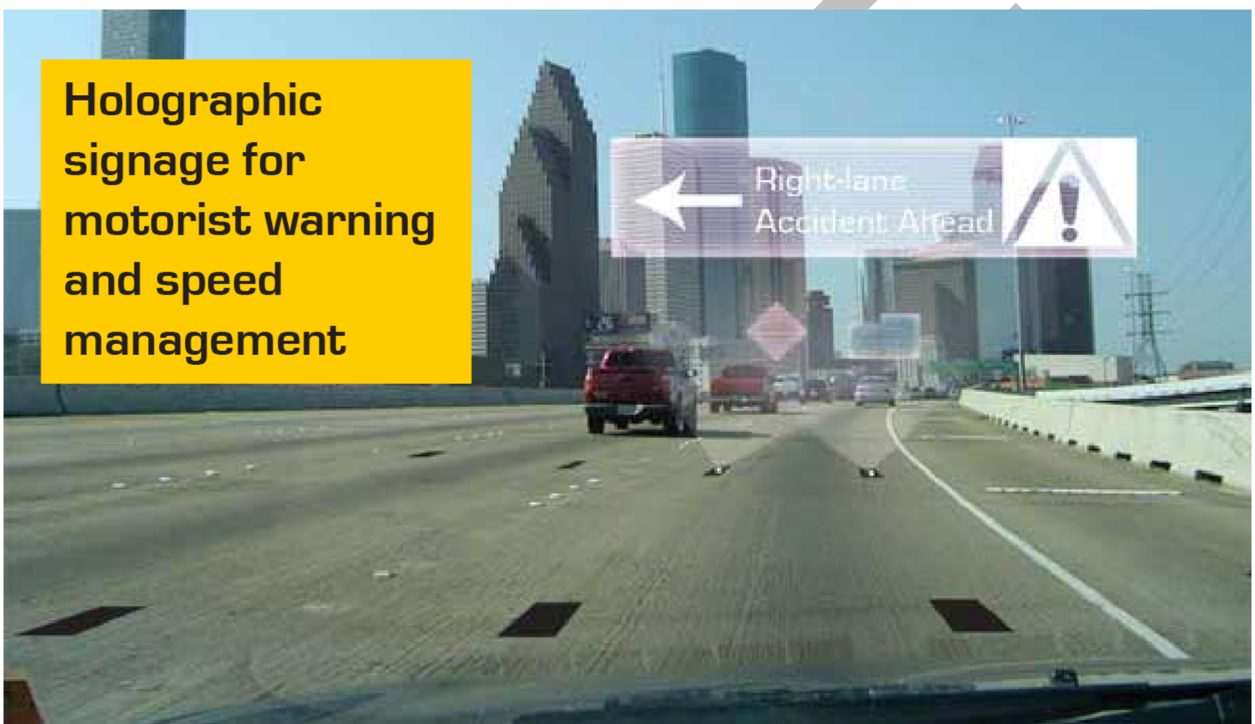
Advance Traffic Warning

Dynamic signage would provide advance traffic warning to drivers unaware of conditions ahead. Rather than relying on poor visibility, information can now travel upstream to the driver. This creates the coordination that improves reaction time and allows for early evasive maneuver if needed. The urgency of the information can be reinforced by physical feedback provided by the pavement device.

The hovering display is possible with multi-angle projection from adjacent devices. Based on laser interferometry, the technology was developed recently and will be available commercially in television sets. The light rays focus on a single plane as to be visible to the approaching driver. The so-called "holographic effect" creates an illusion of the physical signage, which can appear to move or rotate to gain the attention of the driver. The signage would appear semi-transparent so that it does not adversely affect visibility. Different information may be displayed depending on the vehicle speed and spacing, which can include the following information:

- Construction warning
- Lane closure warning
- Speed limit
- Alternate route
- Accident avoidance

By averting just 10% of motorist fatalities, a city similar to Los Angeles can save $300M/yr from avoiding 10% of the ~1100 traffic fatalities that occurred 2014.



Dynamic Light Display (DLD) for roadway signage and advance warning

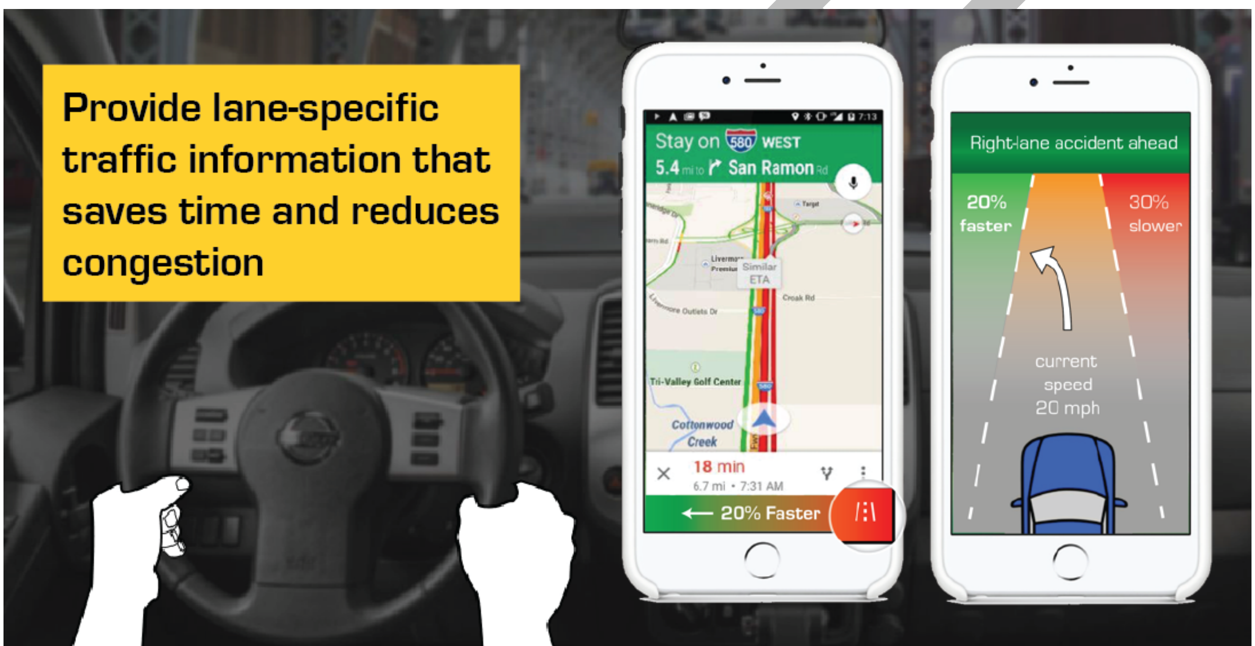
Mobile Connectivity
Cameras are inaccurate, maintenance heavy and expensive to install. GPS sensors that locate mobile devices are slow and inaccurate to the dimension of lane spacing. These shortcomings limit the applicability of mobile apps to provide low-latency, lane-specific information to drivers. If they were available, traffic speed for express and normal lanes would be available. Commute times would be more accurately predicted. Emergencies of lane-closure and accidents could be made in advance to drivers. These improvements make better use of the roads, increase traffic coordination for cars with and without drivers, and can uniquely identify vehicles for congestion tolling or other price-signal schemes.

Virtual Parking Assistance
Traffic experts estimate that 19 to 34 percent of cars in urban streets are looking for parking, causing driver distraction and creating roadway congestion. Luckily, new research points out that parking in U.S. metro areas is, on average, over supplied by 65 percent. A study of mixed-

use districts across U.S. cities found “parking was universally oversupplied.” Those studied include 6 cities in New England and California.

The Adaptive Pavement can detect and communicate empty city spaces to the cloud. Drivers can then use mobile devices to locate and reserve public spaces. With the rise of self-driving taxis, an empty parking spot can share its location to those vehicles not in service, such as when waiting for customers or having mechanical issues.

Cutting time and frustration for drivers who are looking for parking can reduce volume, alleviate congestion and improve pedestrian safety.



Integration with traffic map and navigation apps

1.4 User Acceptance

The adoption of Adaptive Pavement can greatly improve convenience, safety and mobility, the three tenets of effective transportation. In tangible terms, the expected satisfaction for the proposed system can be measured by the cost savings generated. In Los Angeles county, the annual savings would accounts for ~$1,500 per driver. This figure is derived based on the estimates of recoverable loss of productivity, time and fuel.

In addition, the indirect benefit includes savings of ~$10 Billion generated from the avoided new constructions and land acquisition that would otherwise have been funded through local tax hikes. The relatively low cost of the retrofit, ~1% compared to roadway expansion, also makes fast, equitable improvements possible. Overall, making existing road stock adaptable to real-time traffic conditions would yield tremendous taxpayer satisfaction and bring value to the local economy.

Conclusion

Unlike standalone mobile apps, hardware solutions can smart-ify infrastructure by combining real-time data with signaling and enforcement. Data sharing on pedestrians and motor vehicles would create new opportunities to improve safety and mobility. New light projection technologies could enable holographic displays as dynamic signage. Then, real-time information can forewarn drivers of emergencies and enforce dynamic speed limits. Overall, the technology will create a new smart infrastructure based on:

- Unimpeded signaling for pedestrian and motorists at busy intersections
- Greater coordination between vehicle to mitigate stop-and-go traffic
- Broader Interconnectivity for data-sharing and data-as-a-service platforms

To relieve congestion, Adaptive Pavement would form a network of dynamic “speed bumps” that can provide haptic feedback to the drivers. The self-adjustment is made through the detection of lane-specific speed and volume information. During peak traffic, peak throughput can be maintained at the ideal speed of ≈40 mph. Even with unexpected accidents, active road feedback could slow the approaching traffic *miles* ahead to prevent the choke point from occurring. These and other key advantages of the technology include:

- Dynamic pavement able to diffuse congestion and adapt to real-time traffic conditions
- Direct visual and haptic feedback to motorists for advance traffic warning
- Effective safety countermeasure for reducing vehicle speeds en masse
- Intelligent data analyzer for lane-specific information on vehicle type, weight, and speed

Taxpayers would benefit from reduce traffic congestion, improved safety and mitigated carbon pollution. With 10% market penetration to the busiest corridors, the economic benefits In lieu of spending billions on roadway expansion[4] would include:

- ~$1,500/yr saving[5] per driver through alleviated congestion in SF and LA
- ~$80M savings in recovered economic productivity
- ~$990M savings in averted car crash fatalities (assuming 10% averted)
- ~$1.0B savings in averted collision damage and body injury claims (10% averted)

To proceed, the project team will seek partnership from CALTRANS and SFMTA for pilot-scale demonstration. The efforts will consist of the following business milestones:

- Demonstrate potential net savings to utility ratepayers and transportation authorities.
- Optimize performance benchmark with continued product iterations.
- Seek smart city partnerships with municipalities and launch product.

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