The Exploratory Advanced Research Program

EXPLORATORY ADVANCED RESEARCH

Back-Casting Breakthrough Research in the Transportation Sector

RESEARCH SUMMARY REPORT

U.S. Department of Transportation
Federal Highway Administration

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16. Abstract
This report presents a historical analysis of breakthrough research in highway transportation on behalf of the Federal Highway Administration Exploratory Advanced Research Program. It illustrates how transportation-related breakthroughs emerge from long-term, high-risk research. This project addressed three questions: how often breakthroughs occur; when are research advances recognized as breakthroughs; and what allows for the widespread adoption of a breakthrough. The project evaluated candidate projects and identified five breakthrough developments for in-depth study: ramp metering, tunnel boring machines, electronic toll collection, rumble strips, and mechanistic-empirical pavement design. The report draws four conclusions. First, research breakthroughs require an environment of sustained public-sector support for research. Second, breakthrough research outcomes offer solutions to vexing transportation problems and clear benefits for end users. Third, research breakthroughs build on and combine related technological developments across multiple disciplines or by combined expertise across fields. Fourth, breakthroughs require iterative experimental studies and pilot deployments to help ensure widespread acceptance.

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SI* (Modern Metric) Conversion Factors

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	654.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	meters	L
ft^3	cubic feet	0.028	meters	m^3
yd^3	cubic yards	0.765	kilometers	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9	Celsius	°C
		or (F-32)/1.8		
		ILLUMINATION		
fc	foot-candies	10.76	lux	lx
ft	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yard	yd^2
ha	hectares	2.47	acres	mi
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	mililiters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candies	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	ft
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Introduction

The Federal Highway Administration's (FHWA) Exploratory Advanced Research (EAR) Program focuses on longer-term, higher-risk research with a high payoff potential. This report summarizes a project conducted by the U.S. Department of Transportation to better understand how transportation-related breakthroughs emerge and help the EAR Program assess the potential impacts of research results.

As the word suggests, a breakthrough is a step increase in technological development that allows the industry to move through or overcome a barrier. Breakthroughs are not gradual or incremental improvements. Instead, they occur when a fundamental aspect of the technology is significantly changed, when two or more previously unlinked technologies are combined to provide a valuable application, or where a previously unsolvable and important problem in the field is resolved in a manner that can be replicated and deployed.

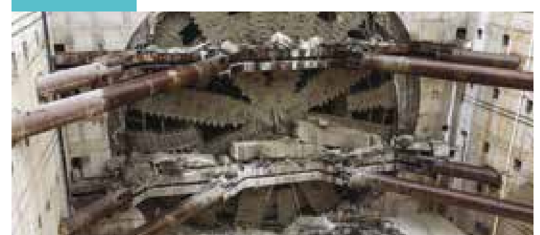
The project's research team identified a candidate list of historical breakthroughs in highway transportation (Appendix 2). The researchers explored the research trajectory for each breakthrough, as well as the political, economical, and institutional conditions surrounding their development, testing, and implementation. The breakthroughs cover a wide range of innovations in surface transportation, are well established, and occurred within the past 50–100 years. The research team selected five breakthroughs for deeper analysis:

- Ramp metering;
- Tunnel boring machines;
- Electronic toll collection;
- Rumble strips; and
- Mechanistic-empirical pavement design.

This report provides a better understanding of how transportation-related breakthroughs emerge from long-term, high-risk research so that the EAR Program and other research and development programs can hone their assessments of potential impacts, from the selection of topics to the transitioning of Program results through applied research. The results from this exercise could assist in setting realistic expectations about the time and paths, from scientific and technology breakthroughs to implementation.

1 Ramp Metering

2 Tunnel Boring Machines



3 Electronic Toll Collection

4 Rumble Strips

5 Mechanistic-Empirical Pavement Design

Figure 1. Photo. Ramp metering system uses traffic signals to regulate the flow of vehicles entering a freeway from on-ramps. ©Washington State Department of Transportation.

Case Study: Ramp Metering

Ramp metering is a freeway management technique that reduces congestion by regulating the flow of vehicles entering the freeway from on-ramps, typically using red and green signal lights. The advent of ramp metering in the 1960s represented a technological breakthrough in freeway management. In the preceding decades, transportation planners made strides in upgrading the safety and efficiency of America's highway network through such improvements as paving, grade separation, and access control. But as a nationwide network of interstate highways became a reality, so did congestion on urban freeways. Though the idea of driving without stopping resonated strongly with the motoring public, traffic managers nevertheless began to consider the seemingly contradictory idea of adding traffic signals to the freeway system.[1]

As early as the mid-1950s, initial efforts to reduce congestion by building new freeways failed, particularly in large urban areas.[2] As a result, there was increasing interest in alternative approaches. FHWA funded several surveillance experiments in the early 1960s—specifically, the Highway Planning Survey Program—to test the impacts of new approaches. Among these experiments was a ramp metering trial in the Chicago area, led by the Illinois Department of Transportation (IDOT). IDOT installed the first ramp meter in spring 1963 on the Congress Expressway.[3] An evaluation of the ramp metering experiment indicated modest but noteworthy improvements to speeds and flows on the expressway. Surface streets saw lower speeds and higher volumes, but the overall net impact on the combined arterial-expressway system was positive.[3] Starting with a single experiment in the Chicago area in 1963, ramp metering has grown to cover approximately 2,800 on-ramps in metropolitan areas across the country, representing about 14 percent of all on-ramps among surveyed agencies. Numerous evaluations have shown that this relatively simple operational treatment can produce significant improvements in freeway flows, speeds, and crash rates.[4,5]

Case Study: Ramp Metering cont.

Ramp metering is related to an emergent set of roadway operation and design techniques, including speed harmonization and modern roundabouts, which emphasize net gains to the overall traffic system, even if some individual users experience delay. If properly implemented and calibrated, ramp metering limits the number of drivers who access the main roadway at any given time, thereby reducing urban freeway congestion.[6] Ramp metering has become more sophisticated over time, notably a move from fixed-signal timing to traffic-responsive and centrally coordinated control. Engineers and researchers continue to add innovations, such as improved algorithms that optimize vehicle movement across combined freeway-arterial systems, using real-time status information of traffic and environmental conditions. One of the ways these improved algorithms manifest themselves is through adaptive ramp metering, which uses traffic-responsive or adaptive algorithms that can be optimized based on local (or even system-wide) conditions.[7]

The formal research on ramp metering shows that its impacts vary according to local conditions and that it may not be appropriate in all cases. In general, however, this simple operational treatment has led to substantial benefits. For example, FHWA estimated typical impacts in the range of a 24- to 50-percent reduction in ramp merge crashes, a 17- to 25-percent increase in mainline throughput, and a 16- to 62-percent increase in mainline speeds.[8] Drawing on more recent evaluations, the Intelligent Transportation System Joint Program Office's benefits database cites improvements of 13 to 26 percent in mainline speeds and 6 to 16 percent in overall freeway-arterial system travel times.[9] Ramp metering tends to rate well in terms of cost-benefit analysis, because the significant travel time savings and other benefits outweigh the relatively low operational costs. Nationwide, ramp metering has an annual mobility benefit that represents an economic value estimated at more than $287 million per year.[9]

Ramp metering does have some key technical and sociocultural limitations. From a technical point of view, ramp metering is only beneficial in certain freeway infrastructures—urban freeways in particular—and, therefore, will not likely become universal. Since metering is best suited to conditions where volume is near capacity, it is unable to provide much benefit when volumes significantly exceed capacity or when there are significant delays unrelated to ramp activity. Just as important, adoption of ramp metering has been hampered by cultural expectations of freeway travel in the United States. Ramp meters are often seen as a restraint on a roadway normally associated with a high degree of freedom. Other objections include equity—the perception that ramp metering unfairly benefits drivers coming from more distant suburbs.

Figure 2. Photo. Tunnel boring machine nicknamed "Bertha" being lowered into position to begin 2-mile-long tunnel project in Seattle, WA, July 2013. ©Washington State Department of Transportation.

Figure 3. Photo. Tunnel boring machine cutter head breaking through final section of construction. ©Washington State Department of Transportation.

Case Study: Tunnel Boring Machines

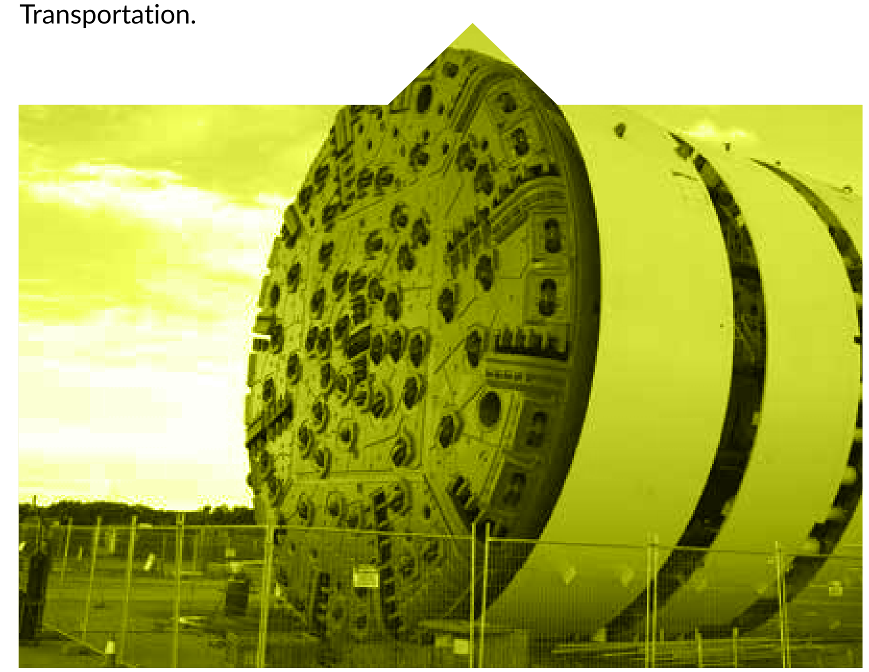
The technological breakthrough of tunnel boring machines (TBMs) required a century-long confluence of innovative design and public investment before it was realized in the mid-1950s. The first successful implementation of a boring machine did not occur until 1953; early prototypes were overly ambitious, underfinanced, and faced competition from cheap manual labor.[10] Development of the technology for TBMs was undertaken primarily by private industry, but public works projects remain the major customer base. TBMs have created efficient new roadways by developing previously impossible tunnel systems, tunneling through the Alps and under the English Channel. They have minimized the surface impacts of burying highways and transit lines in major urban areas. Further, the use of TBMs is not limited to transportation projects; boring machines play a major role in other facets of the tunneling industry, such as for sewers and dams. Today, dozens of TBMs are active around the world at any given time.

Technology for heavy rock tunneling did not advance much further than pneumatic drills and dynamite during the 19th century. The key breakthrough in the development of an early TBM model came from the mining industry in the United States. In 1951–1952, coal mining engineers developed a pick-and-wheel assembly in which a set of metal picks was pushed into the coal face and rotated, creating circular cuts. "Wedging" or "bursting" wheels placed between the picks broke apart the weakened face and carried the pieces to the ground where they were carted away by miners. A tunneling project in Pierre, South Dakota, represented the next advance in TBM design. An engineering firm owned by F.K. Mittry approved the construction and use of a TBM that used continuous scraping and pressure rather than

Case Study: Tunnel Boring Machines cont.

the pick-and-wheel technique. "Mittry's Mole" relied on the pressure and scraping method to bore 160 ft in 24 h, 10 times the speed of drill-and-blast-based tunneling methods. Trial and error with these second-generation prototype TBMs revealed that the cutting face and scraping wheels could bore through most forms of rock. Adding a set of rotating buckets to scoop the rock off the tunnel floor and transfer it away from the cutting face for disposal created the first functional TBM.[10]

In the late 1960s, Chicago committed to a multidecade sewage project, the Deep Tunnel project, which required miles of tunneling beneath much of the metropolitan area.[11,12] Because of the urban nature of the drilling site and the depth and size of the tunnels, the project architects required the use of TBMs. Phase 1 of the project—109.4 mi of drainage tunnels ranging from 9 to 33 ft in diameter and as deep as 350 ft underground—began in 1975, and the tunnel was operational by 2006. Phase 2 is scheduled for completion in 2029, according to the Metropolitan Water Reclamation District of Greater Chicago.[13] Today's TBMs have "smart" cutters that can handle multiple soil and rock profiles across the diameter of the tunnel and can install prefabricated tunnel walls behind the cutter head. The largest diameter (57.5 ft) TBM to date, known as "Bertha," excavated a 2-mi-long tunnel that will carry two lanes of State Route 99 in each direction beneath downtown Seattle, according to the Washington State Department of Transportation.



Tunnel Boring Machines

TBMs permit the construction of tunnels that formerly would have been nearly impossible to build. With TBMs, tunnels can be longer, wider, and farther underground, and they can be constructed with more varied geologies. While they are not always the tunneling method of choice because of their high upfront cost, TBMs provide an option where drilling and blasting is not suitable. TBMs move faster and feature generally safer work environments than drill-and-blast excavation. In addition, they reduce exposure to debris and other environmental hazards, both for tunnel workers and the surrounding population.

Figure 4. Photo. Transponders and cameras built into overhead gantry automate data gathering and toll collection while vehicles move at highway speed. ©Florida's Turnpike Enterprise.

Case Study: Electronic Toll Collection

Electronic Toll Collection (ETC) reduces highway congestion and accidents caused by toll plazas and enables throughput management using pricing. Combining the use of account-linked transponders and license-plate capture for tolls, ETC represents a two-fold breakthrough: first in the use of transponders on the vehicle; and second, the license-plate capture technology that enabled completely toll-booth-free highways. ETC as an innovation breakthrough emerged from the application of a fairly new technology, radio-frequency identification (RFID), to a set of related transportation problems. Though hypothetical systems were described in the 1960s, the first instances of ETC in America were deployed in Texas and Oklahoma in 1989 and 1991, respectively.[14]

ETC allows toll-road operators to collect tolls and alert enforcement agencies of nonpayers electronically, without requiring vehicles to stop at a toll plaza. Without ETC, true congestion pricing (the pricing of road travel based on the current demand for space on that road segment) would be nearly impossible to implement. In addition to enabling congestion pricing, ETC has the potential to lower costs for roadway operators and reduces congestion at toll plazas—improving air quality, travel times, and road safety.[15]

For ETC to become possible, the modern toll road needed to reach some measure of public acceptance, and second, RFID needed to become possible at scale. While toll roads and toll bridges had been seen in the United States since at least the Philadelphia and Lancaster Turnpike in 1795, they required the advent of the automobile and grade-separated highways to become financially viable. Demand was considerable; the Pennsylvania Turnpike earned $3 million (roughly $49 million in 2014 dollars) in 1941, its first year, exceeding the cost of operation

Electronic Toll Collection

Over the past three decades, ETC has gone from a nascent technology to a Federal requirement for toll roads. By the time RFID tags were ready to be commercialized, congestion and funding for road maintenance were becoming important issues that public agencies were willing to take a risk on. ETC emerged from productive exchanges among researchers crossing disciplinary boundaries, which helped to bring RFID technology to the problem of congestion and toll payment. Once deployed, ETC had obvious and calculable benefits.

Case Study: Electronic Toll Collection cont.

and bond payments. Seeing the success of the Pennsylvania Turnpike, many States pressed ahead with their own toll roads. The Connecticut, Kansas, Maine, Massachusetts, and New Jersey turnpikes were all built in the 1940s and 1950s, proving the considerable benefits of grade-separated travel.[16]

Economist William Vickrey envisioned use of an RFID-like mechanism as a tool for seamless toll collection. Vickrey's 1963 scheme included transponders and a cordon-based device system that recorded the number of times a car passed and billed drivers monthly. The earliest use of RFID was during World War II, when British pilots set their radios to a certain frequency when pinged by a ground force to avoid being hit by friendly fire, a technique known as "friend-or-foe identification." RFID-based anti-theft tags, now referred to as electronic article surveillance, became commonly used in libraries and stores by the early 1960s. The key difference between an electronic article surveillance tag and an ETC transponder is the ability to store and send information about the item being tagged. The key centers of demand for this kind of tracking in the 1960s were the farming and railroad industries, which needed to differentiate quickly between nearly identical objects. A final potential predecessor to RFID for ETC was an "electronic license plate" developed in 1974 by Dr. Fred Sterzer at RCA.[17]

The last major innovation in toll collection prior to the development of ETC was the automated toll collection machine, first deployed in 1954 on the Garden State Parkway in New Jersey.[18] The machine reduced operator costs and increased lane throughput. However, violations were common and machines needed to be cleaned out frequently because of other items being deposited besides coins. At least one lane needed to be staffed for those motorists without exact change. Toll-booth congestion remained a fundamental problem of the plazas themselves; the design required motorists to slow down, select a lane, wait their turn, stop to pay, and then merge back into two or three lanes while regaining speed.[19]

In 1989, Texas deployed ETC on the Dallas North Tollway—the first ETC system in the United States. In this case, however, ETC served more as a replacement for the automated toll-collection machine than as a breakthrough technology in its own right. It was added to some lanes in the toll plazas, while other lanes remained available for those without a transponder. Two years later, Colorado and Oklahoma debuted the first examples of open-road tolling (ORT), where those without a pass

Case Study: Electronic Toll Collection cont.

were shunted to a plaza as pass users continued along the roadway without slowing and were scanned by a reader mounted on a gantry. In 1992, California made the first attempt to standardize transponders. In 1995, it opened the first all-electronic toll (AET) road, State Route 91, which was also the first congestion-pricing project in the country. On an AET road, the electronic system replaces all toll plazas and identifies violators through a combination of license-plate capture and physical police presence and enforcement.

These first deployments encouraged the spread of ETC and its use in congestion pricing and the development of the high-occupancy toll (HOT) lane, where single-occupancy vehicles can use extra space in high-occupancy vehicle lanes for a toll. Since the rollout of the AET system on California SR 91, several States have piloted congestion pricing and HOT lanes—among them, Colorado, Florida, Georgia, Maryland, Minnesota, Texas, Utah, Virginia, and Washington. In 2011, the State Route 520 bridge across Lake Washington (connecting Seattle and Bellevue) became the first formerly free route to be variably priced in its entirety, using a combination of RFID transponders and license-plate capture to toll all bridge users at rates that varied with the time of day. Since 2009, FHWA has required all new toll facilities supported by Federal funds to use ETC (U.S. Code of Federal Regulations [CFR] 2014).[20]

AET and HOT systems most clearly highlight the congestion-reduction benefits of ETC, removing toll plazas from the roadway to allow a free flow of travel. Even with toll plazas, ETC users have improved travel times and reliability, while ORT and AET reduce congestion and improve air quality.

ETC is largely commercialized today, with several major providers. Among the key industry concerns is ensuring interoperability among systems, because ETC has grown to the extent that different systems may now be encountered by drivers on the same day. FHWA requires that projects ensure interoperability with nearby systems, to the degree possible, and that projects update their systems as necessary to comply with future rulemakings on interoperability (CFR 2014).[20]

Some factors have limited the adoption of ETC. First, capturing the full benefits of ETC requires substantial changes to highway infrastructure, including highway realignment (must have both a through route and a separate toll plaza), signage, and new toll-booth structure. Second, ETC displaces workers who may campaign successfully against the technology to save jobs. Finally, ETC requires public adoption of the technology, combined with meaningful enforcement. Privacy issues regarding transponders also remain a concern to some users.

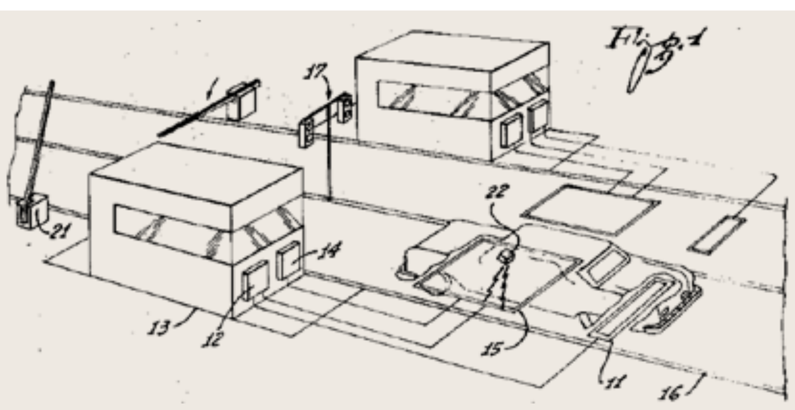


Figure 5. Illustration. Automatic toll charging system, U.S. Patent 3602881. Technology that makes electronic toll collection possible was patented in 1971. Source: United States Patent and Trademark Office, www.uspto.gov.

Figure 6. Photo. Pattern of depressions cut into pavement surface creates sound and vibration to alert drivers who are drifting out of the travel lane. ©Joel Carillet/iStock.

Case Study: Rumble Strips

The breakthrough innovation of rumble strips emerged from concerted experimentation on an existing idea—patterned pavement markings—in a controlled highway transportation setting. Rumble strips are patterned indentations in roadway pavements that alert drivers by generating sound and vibration when a vehicle's tires pass over them. Rumble strips provide a proven safety benefit at a relatively low cost. Continuous rumble strips are now widely placed along roadway shoulders to prevent run-off-road (ROR) accidents, along centerlines to reduce head-on collisions, and across roadways to alert drivers of upcoming hazards such as sharp turns, toll booths, or intersections. Various other names have been used to describe the concept of rumble strips: singing lanes, singing roads, sleeper lines, safety edge, and Sonic Nap Alert Pattern (SNAP). Several U.S. States experimented with rumble strips in the 1950s, with early implementations of rumble strips in travel lanes reported in California and New Jersey as early as 1953.[21] Shoulder rumble strips were first deployed in 1955 along stretches of the Garden State Parkway in New Jersey, but they were removed 10 years later because of a lack of consensus over their effectiveness and concerns about their cost.[22]

The widespread deployment of rumble strips—which occurred in the 1990s—depended on a new technology for milling the strips into the roadway, controlled investigation into their specific design configurations, and cost-benefit studies of their deployment. During the mid-1980s, researchers recognized three research gaps related to the cost-benefit of rumble strips. First, nearly all rumble strip studies focused on areas where the occurrence of ROR crashes was known or presumed to be high. As a result, rumble strips' effectiveness on "average" roads was not generally measured. Second, these studies introduced concerns over maintenance and cost: PennDOT found the strips a "debris catch-all," and California's interchange-loop rumble strip trial was discontinued because of expense.[21] None of the studies

Case Study: Rumble Strips cont.

attempted to rigorously measure the cost-benefit of the treatments. Finally, while several rumble strip implementation sites experimented with a variety of surface treatments, no concentrated effort was made to differentiate among the effectiveness of varying treatment types.

The breakthrough of rumble strip technology into its current widespread adoption resulted from the next generation of carefully studied implementation efforts, led primarily by the Pennsylvania Turnpike Commission in the late 1980s. The Commission identified drift-off-road (DOR) accidents as an increasing problem and began in 1987 to experiment with rumble strips as a possible solution.[23] The Turnpike's snow-plowing requirements prevented the use of raised rumble strips tested in previous trials, so the Commission began investigating recessed patterns that could be rolled or raked into the pavement.

The Commission's tests of milling procedures proved successful and offered the additional benefit of increased in-car noise generation over rolled-in patterns. At about the same time, evaluations of the initial 18-month, 7-mi deployment of SNAP indicated a 70-percent decrease in DOR accidents and no complaints about debris or water retention.[23] As a result, the Commission initiated plans to deploy SNAP across the State's Turnpike system and carefully evaluated the results. SNAP's initial success reinforced the use of milling, and the Turnpike Commission accelerated installation, focusing specifically on milled-in strips that could be retrofitted to existing roads. As a result, 80 percent of the Turnpike had been retrofitted by the end of 1994.[23] This system-wide rollout also led to rapid cost reductions in early SNAP installations, coincident with new innovations in the milling procedure that allowed continuously moving milling machines to cut multiple SNAPs at a time. The cost of one SNAP unit fell from approximately $1 per foot of roadway in 1991 to $0.30 just 3 years later.[24]

The Commission also investigated the milling procedure for rumble strip installation and the effectiveness of various rumble strip geometries. The Commission's initial tests focused on continuous strips, as well as varying depth (between ¼ and ½ inch) and width (between 2 and 4 inches). Only the ½-inch-deep by 4-inch-length pattern generated measureable noise levels in truck cabs. In all tests, spacing between strips was set to 12 inches (center to center), and the width of the strips (perpendicular to vehicle travel) was 16 inches.[23] The Turnpike's adoption of the milling procedure in 1993–1994 meant that the strip width needed to be extended to 7 inches to allow the milling head to

Rumble Strips

Modern, continuous shoulder rumble strips introduce a clear safety benefit for ROR crashes that far exceeds their cost of installation. Many studies of the effectiveness of shoulder rumble strips indicate that they can reduce overall crashes by 14 to 17 percent. Further, shoulder rumble strips have been documented to reduce ROR crashes by 7 to 41 percent. Centerline rumble strips may reduce head-on crashes by 21 to 68 percent.[25] Critically, rumble strips are crash prevention rather than crash mitigation devices: if rumble strips function correctly, an accident can be avoided altogether.

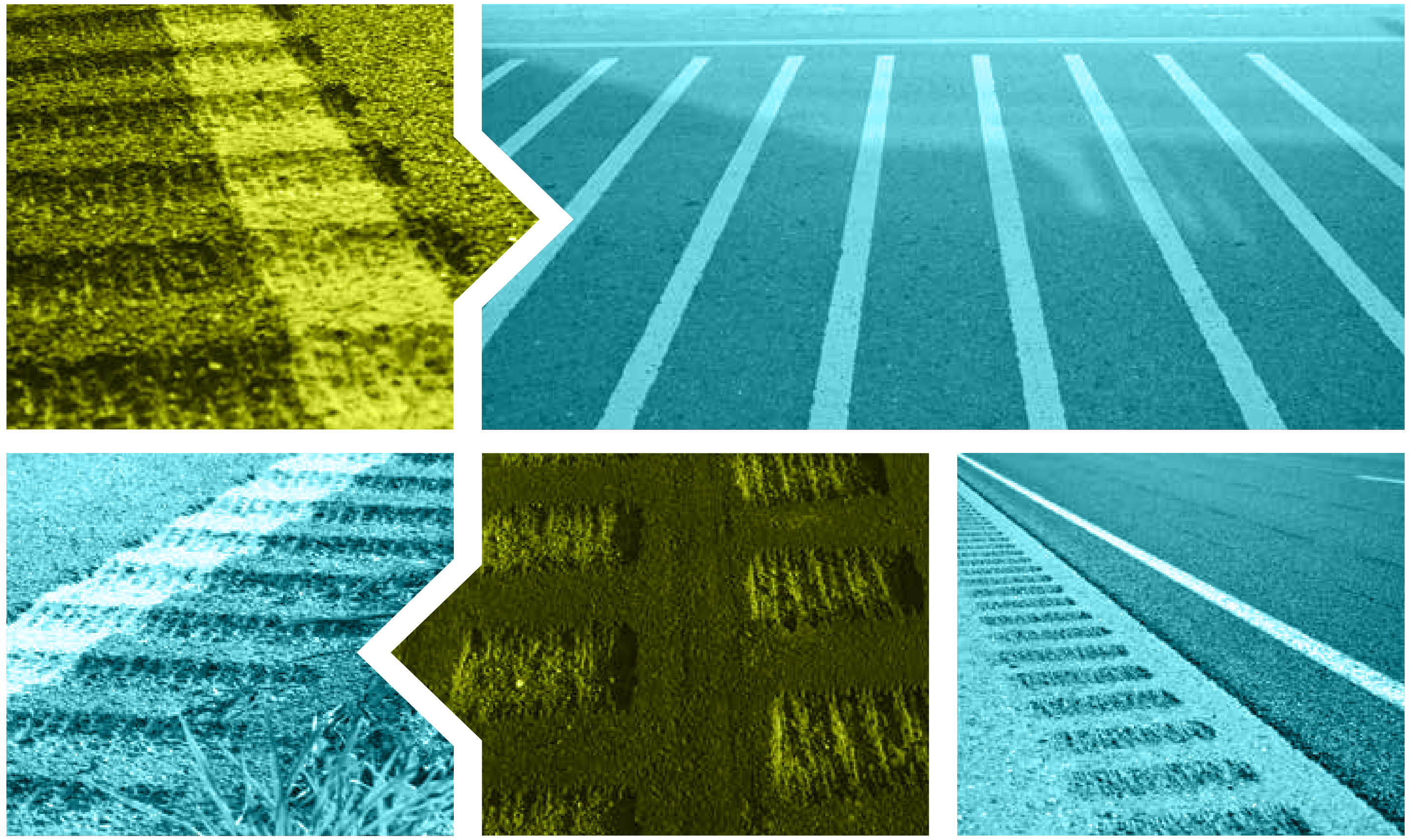
Case Study: Rumble Strips cont.

reach a ½-inch-depth at the center of the strip.[24] The standardized placement of a rumble strip 4 inches from the roadway edge lines was also finalized in these tests.[23]

When the Commission presented its initial findings on rumble strip technology to the Transportation Research Board in 1994, it generated both interest and questions regarding statistical significance, traffic exposure, control segments, and "accident migration."[24] Researchers for a set of rigorous follow-up studies confirmed the positive impact of rumble strips, estimating a 65-percent reduction in DOR accidents attributable to the technology. Investigators of further research documented a 60-percent reduction in accidents on roadway segments with rumble strip installations.[24]

Other States quickly began to install and evaluate the technology. Researchers for a New York State Thruway study produced a cost-benefit estimate of $182 in benefits for every dollar spent on the technology. They also estimated a further decrease in rumble strip installation cost to below $0.20 per foot, which included milling, sweeping, and maintenance.[25] FHWA took note of these study findings and distributed them to all FHWA division offices, beginning a policy push for widespread adoption of rumble strip technology.

Rumble strips are now so widely recognized as a form of driver feedback that several vehicle manufacturers use similar "artificial" vibrational feedback in their lane-departure warning systems. However, some stakeholders have expressed concerns about the impact of rumble strips on cyclists, including both bicycle and motorcycle riders. Though most highways prohibit the use of bicycles, New York State DOT conducted tests to ascertain that the preferred rumble strip design did not present a danger to cyclists.[25]



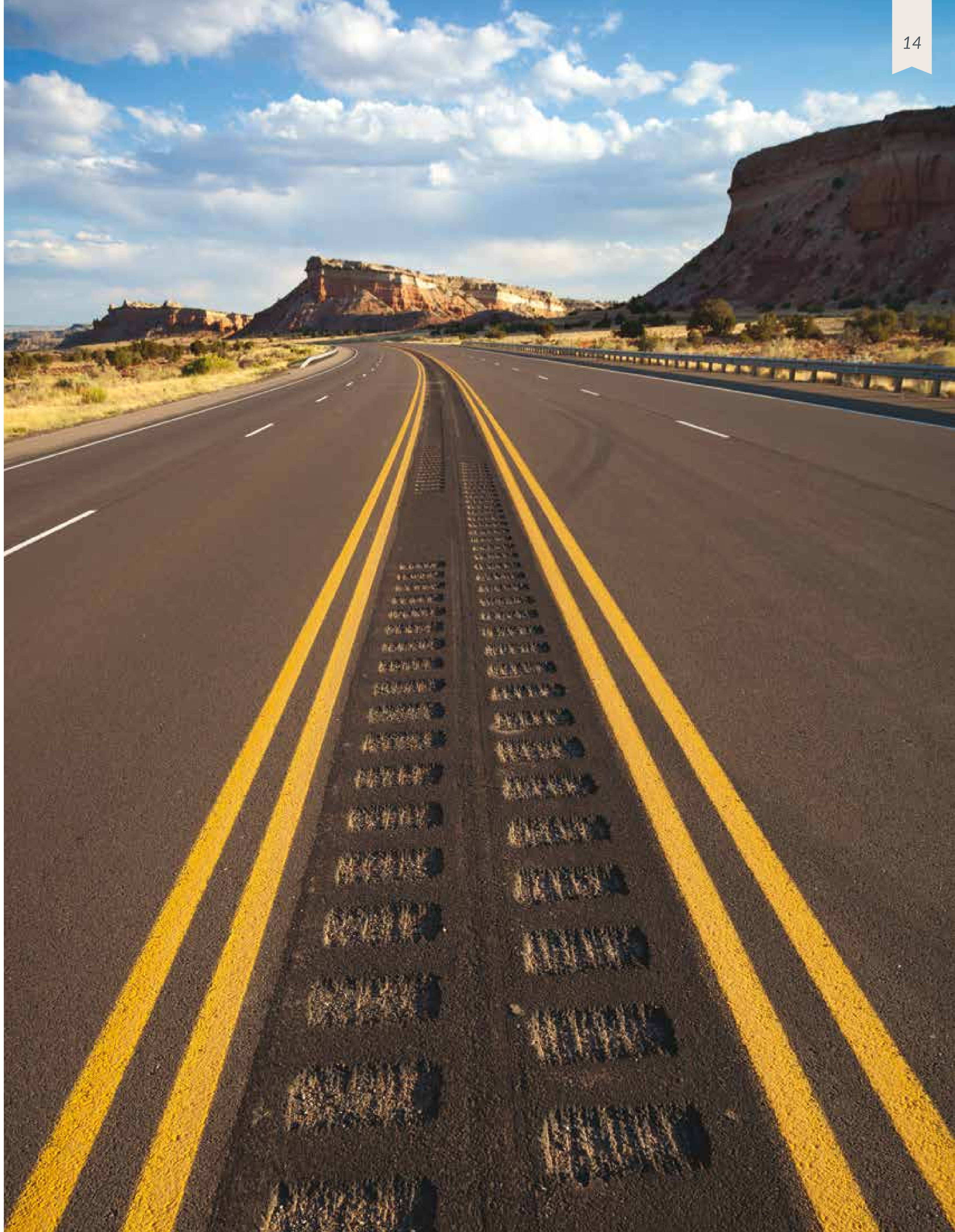


Figure 7. Photo. Example of severe pavement surface cracks and spiraling caused by weather conditions and vehicle weight wear and tear over time. ©undefined/iStock.

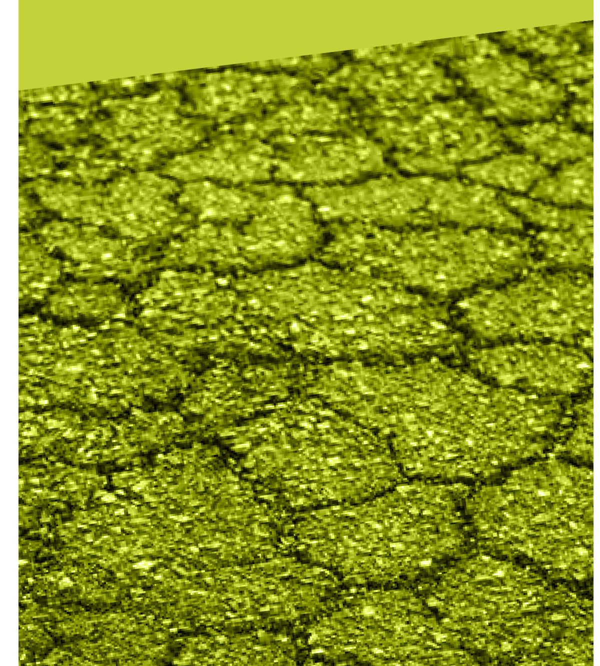
Case Study: Mechanistic-Empirical Pavement Design

Mechanistic-empirical pavement design (MEPD) represents a significant breakthrough in the structural design of roadway pavements. MEPD combines advanced mechanical theory and modeling of physical causes of stresses in pavement structures with empirical analyses to fill in existing gaps between the theory of mechanics and the performance of pavement structures.[26] The design method enables pavement engineers to more accurately predict the performance and durability of pavements. Because MEPD combines field performance data with theoretical prediction models about pavement materials, it allows for a rapid analysis of the influence of changes in pavement materials, traffic, climate, and other important inputs. As a result, roadway pavements using MEPD are more reliable, require less material, reduce costs, have higher longevity, and improve safety compared with previous design methods.

Early research generated simple equations relating concrete pavement thickness to traffic loading.[27] In 1930, the Portland Cement Association adopted the equations in its guidance for design and construction of concrete pavements.[26] However, these early equations and methods were unable to predict the nonlinear and inelastic cracking, permanent deformation, and other distresses affecting pavement systems.[28] Development of MEPD required the integration of mechanistic design theory into the existing empirical design concept introduced in 1960. Prior to the adoption of MEPD, planners relied on engineering experience entirely based on empirical equations derived from the American Association of State Highway Officials (AASHO) Road Test, which took place from 1958 to 1960 in Ottawa, Illinois. Follow-on mechanistic research in the 1950s and 1960s suggested more complex strain calculations to improve predictions of pavement failure. The Shell Oil

Mechanistic-Empirical Pavement Design

Successful breakthrough of MEPD was the result of long-term pavement design research and a steady and continuous accumulation of mechanistic concepts and theory. The implementation of MEPD benefitted from the advancement of computational power and widespread availability of computers capable of running complex mechanistic analyses and calculations. MEPD now incorporates powerful, well-supported, and user-friendly software that is widely used by State agencies.



Case Study: Mechanistic-Empiricial Pavement Design cont.

Company and the Asphalt Institute pioneered use of the linear-elastic theory of mechanics to compute structural responses in combination with empirical predictions of flexible pavement failures.[29,30] However, these prototype mechanistic-empirical methods were still hindered by their limited ability to predict performance of pavements without a sufficiently large base of empirical data.[26] While several States—Minnesota, North Carolina, and Washington—began to develop MEPD procedures independently, the initiation of an extended nationwide survey of pavement conditions in 1989 provided the empirical data necessary for truly functional MEPDs.[26]

Researchers used field data observed during the Road Test to determine empirical relationships for structural designs based on expected loading (axle loads) over the life of a pavement. These relationships allowed engineers to better estimate pavement thickness and design requirements and develop the concept of pavement serviceability, which is based on the premise that roadway pavements should be safe, smooth, and provide a comfortable ride. Meanwhile, road test crews took physical measurements of pavement condition, measuring roughness generated by cracking, rutting, and spalling of pavement surfaces. The statistical relationship between these two measurements—one subjective and one physical—allowed for a present serviceability index, which permits pavement serviceability to be determined by physical roadway inspection.[31] Based on results from the Road Test, AASHO published its first *Interim Guide for the Design of Rigid and Flexible Pavements* in 1961. AASHO— now known as the American Association of State Highway and Transportation Officials (AASHTO)—periodically updates the data.

Limitations of empirical pavement designs emerged. First, roadway and traffic conditions on U.S. roadways changed drastically over time. Commercial vehicle traffic alone has increased up to 20 times since 1960. Original pavement designs were designed for 5–15 million trucks, whereas today highway pavements must be designed for 50–200 million trucks, according to the National Cooperative Highway Research Program.[32] In addition, truck axle configurations, tire types, and tire pressures have all changed substantially since the 1958 Road Test, producing different pavement wear patterns.[32] Finally, the Road Test did not undertake or measure pavement rehabilitation procedures. While the initial Interstate Highway System used pavements designed to last 20 years, modern highway pavements have a design life of 30–50 years and are maintained by routine pavement repair and rehabilitation.[33]

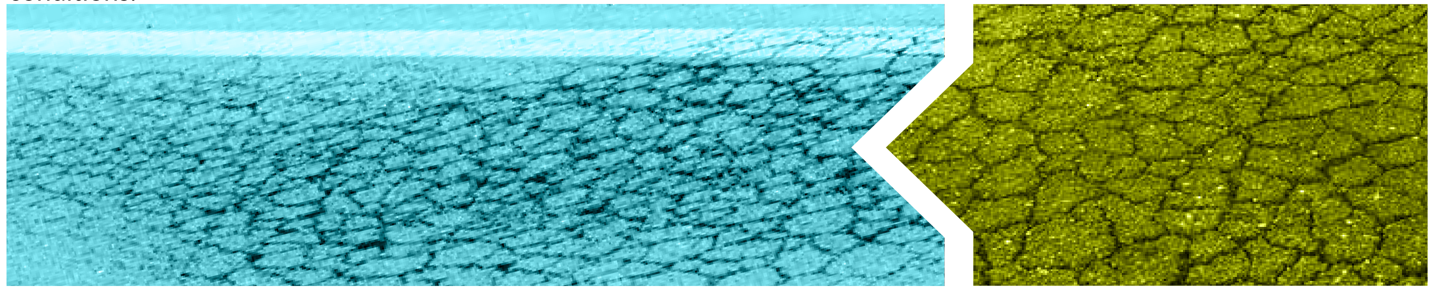
Case Study: Mechanistic-Empiricial Pavement Design cont.

Meanwhile, public demand for safer, quieter, and smoother roadway pavements has steadily increased. Pavements with poor serviceability increased vehicle operating expenses for all drivers—an estimated $222 per year, per vehicle in 2005.[28] By 2005, freight ton-miles had risen over 400 percent from 1970 levels, and 11,000 mi of U.S. roadways—including much of the original interstate highway pavements—were approaching the end of their service lifetimes.[34] Any updates to pavement design guidelines needed to take into account several decades worth of developments in pavement materials, construction procedures, and changed traffic characteristics.[28] Although mechanistic-based pavement design principles had advanced considerably since the 1958-1960 Road Test, the necessary data on pavement performance to support mechanistic analysis models were still not available. To fill this gap, the U.S. Congress in 1987 funded the Long-Term Pavement Performance (LTPP) program, with three objectives: (1) collect and store performance data from many in-service highways; (2) analyze these data to describe how pavements perform and explain why they perform as they do; and (3) translate these insights into knowledge and usable engineering products related to pavement design, construction, rehabilitation, maintenance, preservation, and management.[35] Over the next 20 years, the LTPP program monitored the performance of nearly 2,500 in-service pavement test sections throughout the United States and Canada, representing the wide range of climatic and soil conditions on the continent.[4] Conveniently, this was just the data needed to catalyze a technological breakthrough in mechanistic-empirical design, which demanded highly detailed information about pavements with varying structural compositions across a wide range of loading, climate, and subgrade conditions.[33]

Combining advanced mechanistic design research with the vast datasets of real-world pavement conditions from the LTPP, AASHTO initiated a planning process in 1996 with cooperation from NCHRP and FHWA to formalize a new AASHTO-certified MEPD procedure. The project resulted in the production of formal MEPD procedures in the form of a guide and its accompanying computational software. Upon the MEPD guide's initial 2004 release, AASHTO launched a full program of technical, training, and marketing activities to advance the guide's full adoption. MEPD deployment began in 19 lead States.[36] AASHTO officially adopted MEPD as the new standard in pavement design in 2007.

MEPD provides more reliable predictions of pavement performance across a range of characteristics than the previous empirical design procedure. It produces more accurate pavement design recommendations, based on more than 100 total inputs and data from more than 800 weather sites.[37] It is adaptable to changes in construction materials, traffic patterns, vehicle types, and tire types and configurations, and it facilitates the evaluation of new materials more readily than empirical design procedures. MEPD also reduces lifecycle costs.

While adoption of MEPD required extensive retraining of pavement engineers, as well as new computer systems to run the necessary software, the improved pavement designs produced by MEPD procedures clearly benefit public road agencies and roadway users. In addition, MEPD procedures enable pavement contractors to better judge projected pavement performance and guarantee their work. Finally, MEPD provides forensic capabilities to both public agencies and contractors to resolve disputes when pavements wear prematurely or fail.



Conclusion

The timeframe for innovative research to breakthrough into wide deployment varied widely across the five case studies and breakthrough technologies. Generally speaking, each of the five breakthroughs underwent development, testing, and refinement over one or multiple decades beyond the time when they were first suggested or described as a concept. For example, although the idea of using patterned pavement markings to reduce roadway departure fatalities was first introduced in the early 1950s and briefly piloted again in the 1970s, it took a sustained and successful testing effort in the early 1990s by the Pennsylvania Turnpike Commission to catalyze widespread deployment of rumble strips. The technological breakthroughs examined in the five case studies illuminate the unpredictability of the path from research to deployment of innovative technologies.

Looking across these case studies, four shared takeaways emerge. These are: (1) breakthroughs require an environment of sustained public-sector support for basic and applied research; (2) breakthroughs represent clear solutions to big problems in the transportation sector, with clear benefits to end users; (3) breakthroughs require a combination of technological developments across disciplines; and (4) breakthroughs require experimental studies and pilot deployments as proofs of concept.

Research breakthroughs ***require public-sector support in the development of the breakthrough to the point of a successful and replicable proof-of-concept pilot deployment***. Across the five case studies, this public-sector support took on a variety of forms, from funding early stage, higher-risk research to reducing the risk of initial field testing and demonstrations. One example of this conclusion is the development of TBMs, whose up-front financial costs suggested a prominent role for public-sector support, as was the case for Chicago's Deep Tunnel project. Though the type and duration of public support varied by technological breakthrough, each relied on sustained Government investment throughout the breakthrough's research, development, and deployment timeframe.

Research breakthroughs also ***offer clear solutions to vexing transportation problems***—congestion, safety, and system costs—***and offer clear and calculable benefits for end users***. Each of the breakthroughs detailed in this report sought to reduce or solve key problems in transportation: run-off-road accidents, freeway congestion, roadway design and upkeep, and infrastructure project safety and efficiency. For example, MEPD guidelines and computer software produced immediate cost savings and improvements in pavement selection and deployment.

Research breakthroughs ***build on and combine related technological developments across multiple disciplines***. Though each of the breakthroughs examined in this report took shape as a single innovative research finding or technology, none of them came about as a result of continued incremental research findings in a single discipline or field. For breakthroughs like ETC, these related technological developments include two or more completely separate fields—RFID and toll-plaza design—with the former having only limited interaction with the transportation sector.

Research breakthroughs ***require iterative development and pilot testing*** to shape technologies to a point at which they are recognized as breakthroughs offering solutions to major challenges in the transportation sector. Stepwise development and testing help ensure that risk-benefit assessment guides the evolution of technologies and thereby help catalyze widespread adoption.

TRL Scale Levels

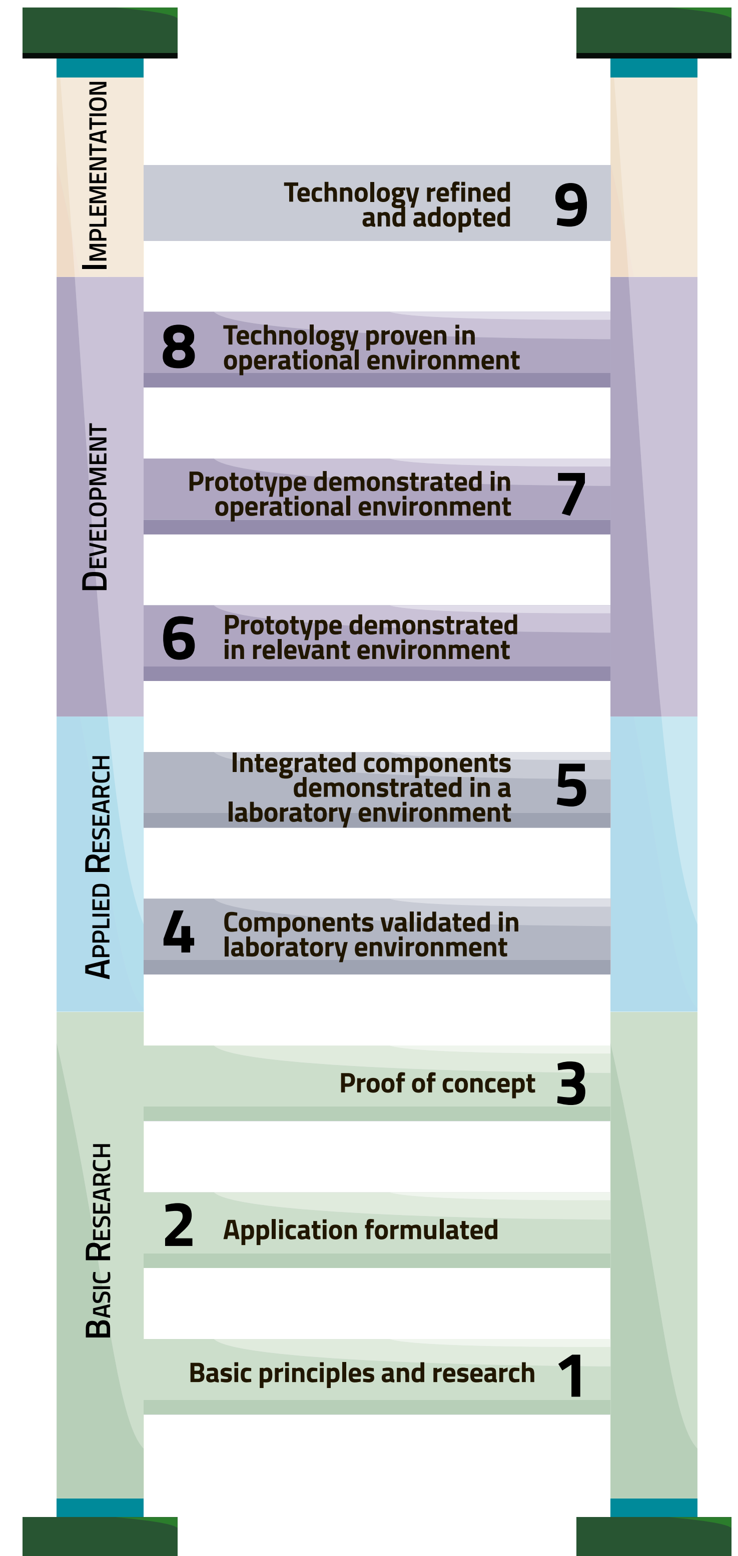


Figure 8. Chart. TRL Scale Levels Ladder Graphic.

Appendix 1: Literature Review

An important element of back-casting breakthrough research in the transportation sector is a comprehensive, multi-disciplinary understanding of what breakthrough research—or technological innovation—is and how it is used. This brief literature review describes several perspectives on technological innovation and situates research breakthroughs in their social and political contexts. The first section of this Appendix lays out a foundational perspective on technological innovation, that of economist Joseph Schumpeter (Dwyer & Zoepf 2011). The remainder of this review of the literature on technological innovation focuses on modern studies of innovation at three levels:

1. Studies of the factors that influence innovation at the firm level
2. Studies of the factors that drive adoption at the consumer or user level
3. Modern studies of technological dynamics that examine trends in technological growth at the societal level.

Early Origins of Innovation Literature: Schumpeter

The study of the theory of innovation traces many of its roots to the work of Joseph Schumpeter, an Austrian-American economist who developed the theory of creative destruction to explain economic development and stability as a function of technological innovation and entrepreneurship. Schumpeter defines development as the introduction of new resources, applications, or processes to the marketplace by "the entrepreneurs" (Schumpeter 1959). In addition to attributing development to entrepreneurialism, Schumpeter also states that development necessarily disturbs the economy from an equilibrium state, and that it does so spontaneously and discontinuously.

The theory of creative destruction attributes commonly observed boom-bust economic cycles to the appearance of entrepreneurial swarms that introduce disruptive innovation into an economy. Specifically, Schumpeter theorizes that booms occur during the introduction of a new swarm and that busts occur as the marketplace absorbs and incorporates the new innovation and struggles to reach a new equilibrium state (1959). He also observes the destructive impact that technology can have on the local business environment. As entrepreneurs introduce innovation, established firms and businessmen may not be able to compete or survive. Meticulously defining innovation as any technological change that results in "'doing things differently' in the realm of economic life," Schumpeter classifies as innovation everything from a technological change in a product or process, to incorporating new sources of supply, to organizational restructuring (1939). He carefully distinguishes innovation from invention by specifying that pure scientific or technological invention does not have an economic impact unless it is introduced to the marketplace. In Schumpeter's view, the entrepreneur serves as the interface between the scientist's invention and the businessman's profit.

The pace of disruptive innovation's introduction into an economic marketplace shapes the extent of the resulting economic upheaval. Schumpeter argues that when innovation occurs too quickly to be smoothly absorbed, it incites a state of economic disequilibrium that affects all firms and industries (1939). During this disequilibrium, firms may discover new opportunities for expansion and growth, may undergo the challenging process of modernization and reconstruction, or may perish. Despite the potential for destruction, Schumpeter argues that this process of adaptation enables the establishment of a successive equilibrium and ultimately results in macroeconomic growth (1939). Looking beyond economic impacts, the theory of creative destruction

Appendix 1: cont.

seeks to link disruptive innovation to broader social and political questions of the compatibility between capitalism and democratic institutions, which is beyond the scope of this report (McGraw 2007).

Business Innovation: Fostering Breakthroughs and Disruptive Innovation at the Firm Level

Numerous business authors explore efforts to foster innovation within a firm. One of the originators of business strategy development, Michael Porter, argues that a firm's ability to succeed in a marketplace is determined by its competitive advantage, which it can maintain by practicing "creative destruction on itself" (Porter 1998). This idea, that innovation within a firm determines its competitive advantage in the marketplace, is echoed throughout literature on business strategy. Most recently, Clayton Christensen developed a theory of disruptive innovation to explain how new technologies developed by small, entrepreneurial businesses can upset market equilibrium and displace established firms (Christensen 2000).

In the field of strategy development, Michael Porter and Henry Mintzberg suggest two frameworks—Porter's Five Force Model and Mintzberg's five organizational structures—as a means to understand firms' internal divisions of labor flows of information and external interfaces to the marketplace (Mintzberg 1973; Porter 1998). By understanding a firm's structure, Porter argues, managers can better realize how disruptive technological innovation will impact the firm and can develop necessary reactive strategies (Porter 1998).

Adoption Theory: Understanding Adoption at the Consumer Level

While firms may attempt to foster innovation through internal structures, investments, and culture, the market penetration of innovations in most cases is also a function of adoption of new technologies by customers and users, be they private consumers, businesses, or governments.

There is a vast body of literature on the adoption of innovations, but many of them use as their basis the Bass diffusion model (Bass 1969). In this model, the process of adoption is seen as a social contagion, where adopters influence other potential adopters via word-of-mouth (Norton & Bass 1987). Additional work in this area has explored the role of multiple generations of products, as well as the role of market intermediaries such as suppliers in "facilitating the flow of information" about new technologies that may impact market adoption (Geroski 2000).

The work of Everett Rogers further expanded study of the adoption of innovations by identifying five key factors that are central to adoption by users (2003):

1. **Relative Advantage:** How well does the innovation perform compared with existing alternatives?
2. **Compatibility:** How compatible is the innovation with existing systems, values, and behaviors?
3. **Complexity:** How difficult is the new innovation to use?
4. **Trialability:** Does the innovation facilitate experimentation with minimal barriers?
5. **Observability:** How easy is it for others to observe the benefits of the innovation?

Apple's iPod is an innovation that demonstrates strong performance on each of these attributes. It offers a large improvement in performance, is highly compatible with

Appendix 1: cont.

existing systems, is simple to use, is easily trialable with low risk, and has benefits that are easily observable by others (Keith 2012).

Additional literature in this area investigates the impact of complex social networks (Granovetter 1973), or where the dynamics of "social contagion" may be more complex (Watts & Strogatz 1998; Centola & Macy 2007). Diffuse networks of potential adopters with distant ties may, in some cases, accelerate the diffusion of innovations as word-of-mouth travels longer distances, but they may hinder adoption as multiple points of contact are required to reinforce the decision to adopt an innovation.

Technological Dynamics: Measuring Technological Progress at the Societal Level

Rather than focusing on attributes of individual producers or consumers, the field of technological dynamics adopts a societal perspective and attempts to quantify long-term changes in technological performance of fields such as transportation, computing, and energy. Early work at the RAND Corporation and other institutions focused on attempts to quantify state of the art in specific fields (Coccia 2005). In the same vein, early technological dynamics research in the 1960s and 1970s attempted to quantify technological change and measures of progress (Ayers 1985). This research discussed technological sophistication and performance in the language of utility and objective functions, a concept reflected later in the notion of functional performance metrics (Ayres 1985; Koh & Magee 2006). In the 1980s, research into technological dynamics began to call attention to the importance of differentiation among structural innovations, material innovations, and systems innovations that arise from two or more "symbiotic technologies" (Sahal 1985). It also pointed to the role of chance in the success of specific technologies as relatively unimportant to the overall rate of progress, a theme seen later in the modern modeling of technological breakthroughs (Farmer & Trancik 2007).

Broadly defined, technological dynamics is a lens through which to study technological advances over time, whether applied to a specific product, process, industry, or other measureable performance attribute. The metrics studied through technological dynamics are fundamental to understanding the influence of innovation. Many authors in the field, including those discussed here, choose case studies from disparate fields: computer microprocessors, refining, power generation, and solar power, to name a few. However, the breadth of the application of technological dynamics demonstrates its power: the concepts of technological advance and the evolution of industries remain remarkably consistent.

Technological dynamics casts innovation as not simply a singular moment but rather as an ongoing process across sectors. For example, management scholar James Utterback suggests that as technologies mature and industries consolidate, the focus of innovation transitions from one of product innovation, with numerous innovative designs, to one of process innovation, wherein products fundamentally look and feel similar, but substantial improvements are achieved in the manufacturing process (Utterback 1996). He suggests that these phases of innovation echo Schumpeter's concept of waves of creative destruction; the impacts of technological innovations are felt not only within the industry or sector they directly affect—the number of competitors in various fields and the level of investment by specific firms—but also society more broadly via their impact to consumers, such as by price reductions over time and improved functionality.

The concept of technology amplification offers a related perspective on innovation, suggesting that a single technology may result in improvements in all interdependent technologies (Farmer & Trancik 2007). As a result, more complex technologies may result in

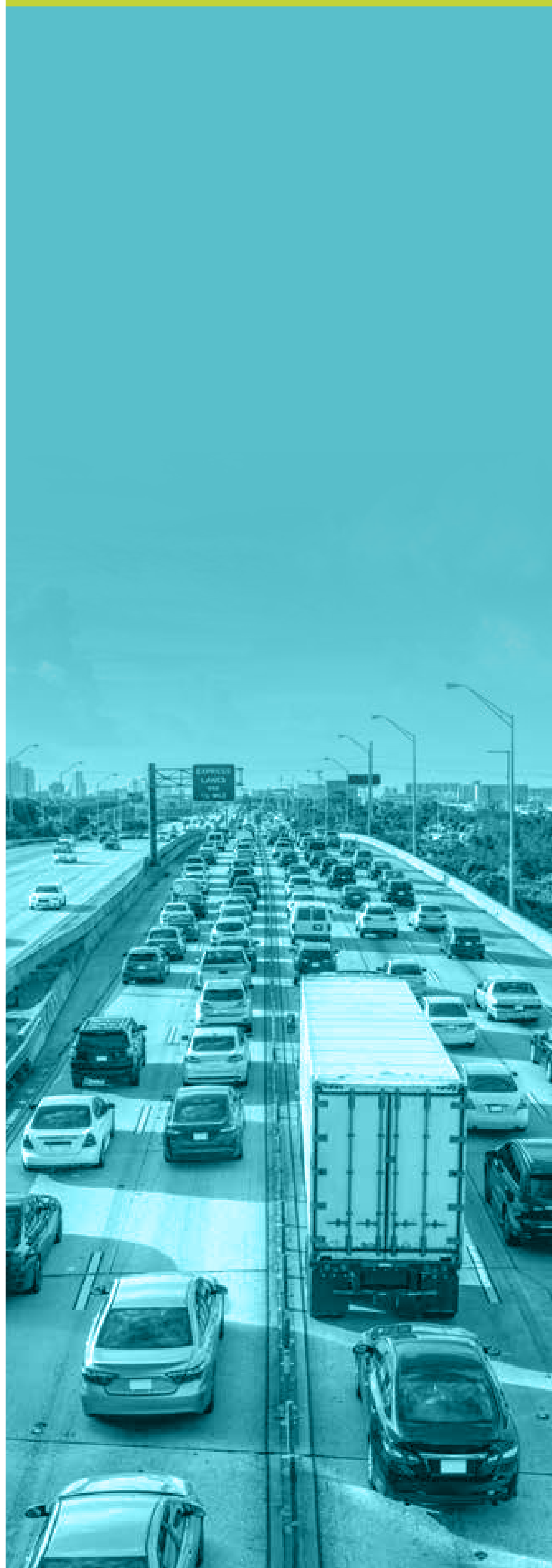
Appendix 1: cont.

greater scales of improvement due to the large number of individual technologies embodied that continue to improve on an individual scale. Furthermore, such technological improvement may form a reinforcing loop; for example, an innovation in semi-conductor modeling will result in better semi-conductors, which will result in better modeling, and so forth (Farmer & Trancik 2007). In such cases, technological innovation forms a natural reinforcing loop that facilitates exponential growth in capability.

Not all scholars of technological change argue that innovation follows such linear processes. Koh and Magee point out that numerous technological fields exhibit predictable growth in performance (2006). They eschew traditional, logistic-curve-based deployment that centers on the deployment of specific technologies or products within a confined market. Rather, by focusing on broad "functional performance metrics" instead of industry-specific measurements, and by examining improvements over time and as a function of cumulative production, Koh and Magee find continuous exponential growth reflecting a Moore's Law-like improvement in each field examined (2006). They suggest that technological evolution is less a function of R&D by specific firms in specific fields, and more as a natural emergent behavior of complex systems.

Conclusion

This brief literature review has sought to describe several perspectives on technological innovation and situate research breakthroughs in their social and political contexts. Though technological innovations may be initially developed in a single sector or firm, the processes by which they diffuse are complex and mostly unpredictable. Ultimately, conceiving of technological innovations as outputs of a complex system of technological dynamics offers a useful perspective on the unpredictability of breakthrough research and technological change.



Appendix 2: Full List of Breakthroughs

INTELLIGENT TRANSPORTATION SYSTEMS	PLANNING AND MODELING	SIGNAGE	ROADSIDE SAFETY	INFRASTRUCTURE DESIGN AND CONSTRUCTION	IN/ ON VEHICLE SAFETY	BIKE/PED/ CARSHARE	ENVIRONMENT	PAVEMENT
ETC and license plate recognition	Routing algorithms	Interstate numbering system	Rumble strips	Single-point urban interchange	LATCH	Bike share	Deleaded gasoline, low sulfur diesel	Superpave
Probe vehicle data	Parking meters	Standardization of highway wayfinding signage	Jersey barriers	Double-crossover diamond interchange	Seat belts and occupant restraints	Car share	Catalytic converter	Stone matrix asphalt
Contactless transit fare collection	Digital mapmaking and spatial analysis	Retro-reflective signage	Impact attenuating sand-filled barrels	Tunnel boring machine	Automated chemical deicing	Segway	55 mph speed limit	Polymer based asphalts
Transit signal priority	TransCAD		Breakaway sign posts and gantries	Onramps	Daytime running lights	iWalk	Corporate Average Fuel Economy	Mechanistic empirical pavement design
Coordinated signal timing	Induced travel							
Ramp metering	Metropolitan planning organizations		Impact absorbing barriers (i.e., ET2000)	Highway cloverleaf structures	Electronic stability control	Tactile pedestrian feedback	Truck stop electrification	Fiber reinforced polymer bridge decks
Variable message signs	Traffic calming				Turn signals		Recycling cars	
Automated vehicles					On-board diagnostics			
Automatic Vehicle Location					Mandatory trunk release			
Apps: Transit								

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