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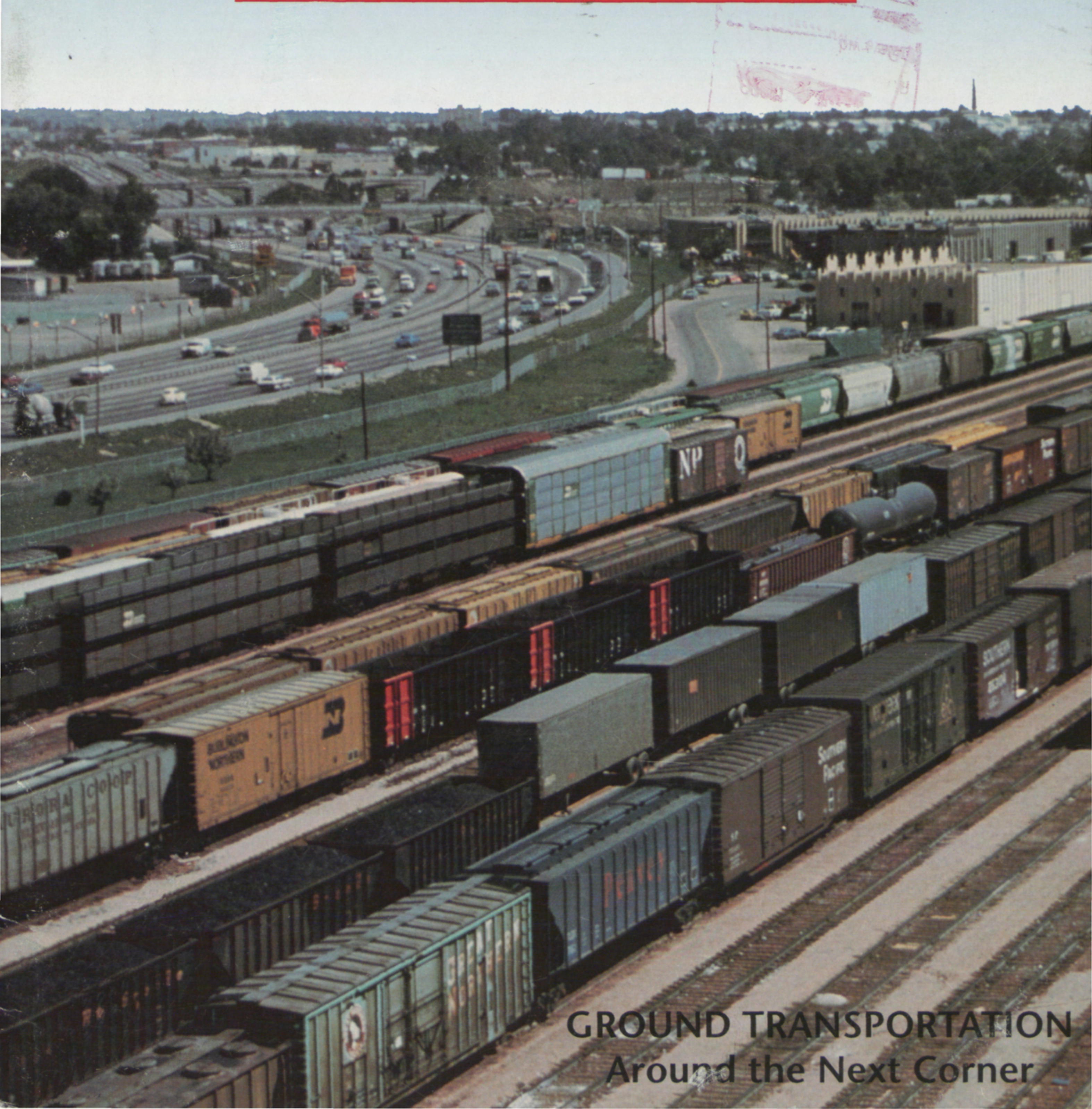
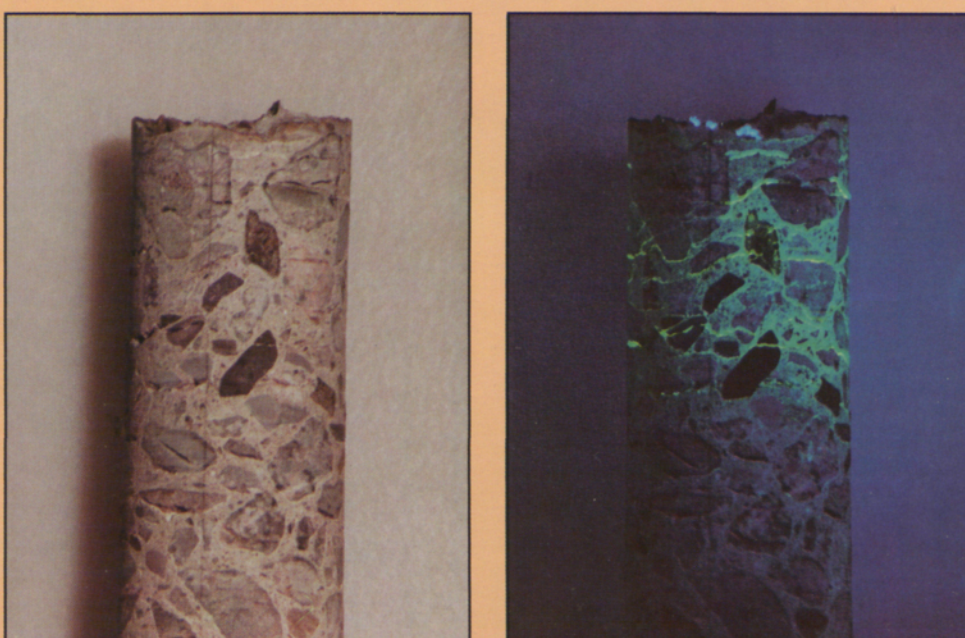


GROUND TRANSPORTATION
Around the Next Corner

The Mark III human-powered vehicle, with zippered fairing in place, cruises on the engineering quadrangle near Upson Hall (story on page 20).



A treated concrete sample is seen by ordinary light (left) and ultraviolet light (right). The greenish-yellow glow reveals cracking due to a chemical reaction between Portland cement and crushed stone (story on page 3).

Robert D. King, a project manager at General Electric Company in Schenectady, New York, built this electric car and drove it back and forth to work for several years. It cruised at 50 miles per hour, had a range of 55 to 60 miles per charge, and cost 1.5 to 2 cents per mile to operate. King is an industrial adviser to the Cornell electric vehicle project (story on page 15).

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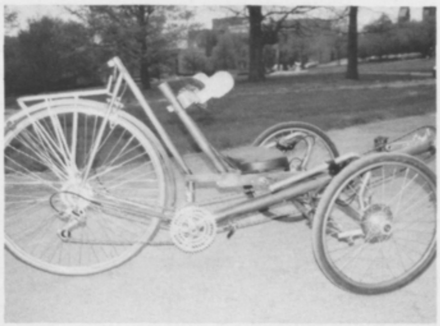

Cover picture courtesy of Burlington Northern Railroad

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GROUND TRANSPORTATION

Around the Next Corner

Transportation is crucial to modern society. With a majority of the population living in cities, an efficient freight transportation system is necessary just to supply food. And with many people commuting to work, an efficient people-moving system is also necessary. Indeed, one of the most striking differences between an industrialized society and an underdeveloped society is how expeditiously raw materials, goods, and people are moved around.

During the forty-five years of the Cold War, defense was a paramount national priority. In colleges and universities—as well as in industry—attention, money, and creativity were focused in a massive way on matters relating to defense. Federal largesse benefitted a whole range of research, some of which did not even have an obvious military application. Now that the Cold War is over, these resources are being scaled back. But the peacetime economy of an internationally competitive industrialized state still depends on technological excellence. What is needed is a change of focus, and one of the first sectors of society that can be improved with the help of engineers is transportation.

Railroads have languished since the Second World War and highways have not been a national priority since the 1970s. Now the nation has thousands of miles of rusting rails, a diversity of dubious bridges, and an interminable procession of constantly reappearing potholes. Even the hegemony of Detroit in manufacturing automobiles seems to have passed overseas.

In the post–Cold War period, engineers will be called upon to help renew the nation's transportation infrastructure. This is both an area to which researchers can turn their endeavors and an undertaking that will provide a market for the talents of young engineers. The Cornell College of Engineering is well positioned to lead in this initiative, and the five articles in this issue of the *Quarterly* call attention to research and educational programs that focus on transportation.

A whole team of specialists in the School of Civil and Environmental Engineering is concerned with concrete, as described in the article by Kenneth C. Hover. Efforts to understand the ways in which concrete deteriorates, to extend its useful life, and to find dangerous flaws are critical to the safety of highways and bridges.

Projects that involve building innovative vehicles are opportunities to train young engineers as well as develop prototypes that may be harbingers of future transportation alternatives. Albert R. George describes the formula SAE program, which gives fledgling automotive engineers practical experience and introduces them to organizational strategies that contribute to industrial competitiveness. John Belina reports on the electric car project, showing how computerized control and space-age components can give an old idea renewed vitality. Samuel Landsberger explains how the human-powered vehicle project introduces mechanical engineering students to the conceptual and social constituents of the design process as they work toward a visionary commuter vehicle that is healthful and nonpolluting.

In an article that focuses more on strategy than materials or mechanics, Mark A. Turnquist shows how the nation's existing transportation system can be made more efficient through the institution of computer-controlled, intermodal scheduling.

Other work in the College of Engineering, not specifically reported on in this issue of the *Quarterly*, also contributes to improving transportation. For may years, Lynne H. Irwin, of the Department of Agricultural and Biological Engineering, has been specializing in local roads—the small, low-cost, low-maintenance roads that enable farmers to get their produce to market. A group of students working under the advisorship of Robert J. Thomas and Richard Warkentin is designing and building a hybrid electric vehicle with an internal combustion engine to supplement battery power. Francis Moon's research with high-temperature superconductors (see his *Quarterly* article, 24(2):17–22) is oriented toward the development of magnetically levitated trains, which, in principle, will be able to run at great speeds by eliminating friction between the conveyance and the surface upon which it travels.

As the Cornell College of Engineering turns the corner into the next century, talented and dedicated faculty members will make it a source of innovations in ground transportation as well as an educational institution of choice for prospective engineers who want to contribute to a peaceful and prosperous future.—DP

COPING WITH OLD CONCRETE

A Team Effort to Maintain Transportation Infrastructure

by Kenneth C. Hover

Motorists inching along in one-lane traffic while construction crews repair bridges might well wonder why "cast in concrete" has become a metaphor for permanence. Concrete is an artificial conglomerate rock, but it does not last forever. Frost, salt, and repeated loading contribute to the deterioration of concrete, and a program of inspection and repair is necessary to keep highways safe.

By and large, the system works. Of New York State's 19,500 bridges, only two have failed catastrophically in the last ten years. This is a remarkably low percentage. While it may be cold comfort to those whose loved ones were lost in these accidents, the reliability of the overall system meets highly conservative quality-control standards.

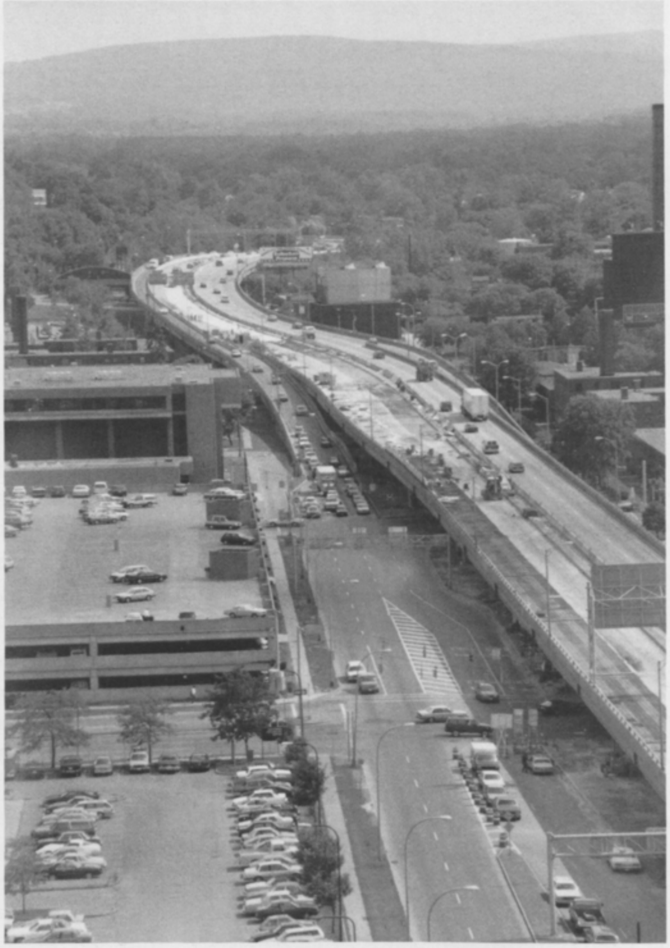
But the number of bridges and pavements in need of repair can be expected to grow. Highways constructed during major road-building programs of the 1950s through the 1970s are beginning to show signs of age. In some parts of the country, maintenance crews cannot keep pace, and bridges may have to be taken out of service because they cannot be repaired fast enough.

What may not be evident to motorists threading their way through a construction zone is that repair crews are preceded by engineers who inspect bridges and pavements to evaluate their safety. Every bridge in the state of New York, for example, must be inspected once every two years. Thorough inspections often require the services of licensed divers with engineering experience to evaluate underwater piers and foundations. As concerned agencies step up the frequency of inspection and the level of detail required, the cadre of qualified inspectors is spread increasingly thin.

"In some parts of the country, maintenance crews cannot keep pace...."

A work crew repairs deteriorated concrete on Michigan Avenue in Chicago.

Right: Recent repairs to Interstate 81 in downtown Syracuse, New York, were made necessary by the corrosion of reinforcing steel embedded in the concrete.



Above: The increased volume of iron oxide products resulting from corrosion of reinforcing steel causes delamination.

Concrete curbs in Breckenridge, Colorado, show the effects of freeze-thaw damage, salt scaling, and erosion.

The Recipe for Concrete: Sand, Gravel, and Cement

Concrete is a composite material that is made by gluing sand and stone together with Portland cement paste. Portland cement is a blend of calcium and aluminum silicates. Iron and a variety of impurities such as manganese give the final product its characteristic brown, gray, or off-white color. To manufacture Portland cement, earth materials including limestone, clay, shale, slate, and alumina are pulverized and heated in a kiln to drive off carbon dioxide and water and to partially fuse the active minerals. The hot mass from the kiln is then ground to a fine powder with particles less than 100 micrometers in diameter.

When Portland cement is mixed with water, a fluid paste is formed. The cement solidifies as the water is consumed in a hydration reaction that produces microscopic interlocking crystals which hold the mass together. The strength of concrete derives from the mutual attraction of electrical charges on the surfaces of these microcrystals.

As the water in the mix becomes water of hydration, the space it originally occupied becomes part of a network of interconnected capillary pores. With time—and provided that extra water is supplied and the concrete is kept warm enough—these pores become blocked by the continued growth of microcrystals. But the most effective way to minimize the pore volume, which is detrimental to virtually all desirable properties of concrete, is to use as little water as possible. Unfortunately, the less water is used, the more difficult it is to handle the concrete. Surfactants are routinely added to increase fluidity with less water, and the size of sand and stone particles can be adjusted to improve flow and packing. But these solutions have a price, and the least expensive, most expedient way to make concrete flow better is, unfortunately, still to add more water.

The Porosity of Concrete and the Mechanics of Degradation

The way concrete deteriorates is a consequence of its porosity. While its apparent solidity is proverbial, so that "solid as concrete" has become a part of the language, under a microscope it looks more like a sponge. Conventional hardened concrete can absorb up to 10 percent of its weight in water, and this is where the trouble starts.

As water enters the pores, the concrete expands, and as it leaves, the concrete contracts. Cycles of wetting and drying lead to fatigue. Further, when water remains in the pores during cold weather, the expansion that accompanies the formation of ice causes scaling and cracking. This *freeze-thaw damage* is a primary contributor to the decay of concrete infrastructure. The effect is intensified when deicing salts are used, for they cause the absorbed water to freeze more quickly, just as the mixture of salt and ice in an ice cream maker rapidly chills the cream.

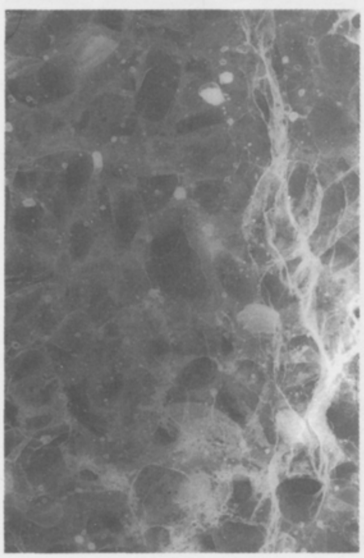
Water also redistributes soluble compounds through the pore system of the concrete. Calcium, sodium, and potassium ions, as well as hydroxyl groups, chlorides, and sulfates move in the water-filled pores, eventually building up harmful concentrations that can dissolve certain types of aggregates, just as strong household cleansers can dissolve opal jewelry. This problem, known as the *alkali-silica reaction*, has become more salient in recent years as a dwindling supply of high-quality natural aggregates has made it necessary to use marginally reactive materials.

A third problem is *chloride-induced corrosion* of the steel reinforcing bars that are embedded in the concrete. Since the late 1960s, the driving public has demanded bare pavement all winter long, and this has led to the widespread use of deicing salts—usually sodium chloride or calcium chloride. (Many products claiming to be "salt-free deicers" are actually calcium chloride, which is more effective, more expensive, and more corrosive than ordinary "rock salt.") When deicing salts are applied to roads and bridges (and subsequently deposited on driveways, parking lots, and parking garages), salt water penetrates the pores of the concrete and eventually arrives at the surface of the internal reinforcing steel. There, the chloride ions accelerate the process of corrosion, leading to the formation of expansive iron oxides that crack and spall the concrete. This has become a primary factor in the deterioration of reinforced concrete bridges and parking structures, making it necessary to repair or replace thousands of bridge decks all across the country.

A deteriorated bridge pier in New York City requires urgent repair.

The bridges carrying U.S. Route 13 over State Highway 34 in Ithaca, New York, required complete replacement of the piers while the bridges continued to carry traffic.

Twin bridges carry Interstate 471 over the Ohio River at Cincinnati. The author was responsible for the concrete construction work in the project.



Internal cracking in concrete is revealed through neutron radiography.

Concrete exposed to sea water or salt spray is also subject to chloride-induced corrosion of reinforcing steel, so that the problem affects coastal highways as well as those in snow-belt regions. Sea water also contains sulfates that may combine with aluminum in the hardened Portland cement, forming expansive crystals that cause the concrete to disintegrate. This *sulfate attack* is also a problem in certain industrial and waste-treatment environments.

Approaching the Problem from Many Angles

A comprehensive solution to the problems of deteriorating transportation infrastructure requires multiple approaches. We need better ways to identify problems in the field. We need better ways to evaluate load-carrying capacity and estimate remaining service life. We need more effective repair techniques and strategies that will minimize down time—and we need innovative ways to accommodate out-of-service facilities until repairs can be made. To break the seemingly endless cycle of reconstruction and repair, we need improved construction materials and methods so that bridges and pavements built today will last longer.

Researchers at Cornell's School of Civil and Environmental Engineering are working on all of these fronts. Special efforts are aimed at developing more sensitive testing techniques, more durable structures, and a better understanding of materials and their behavior.

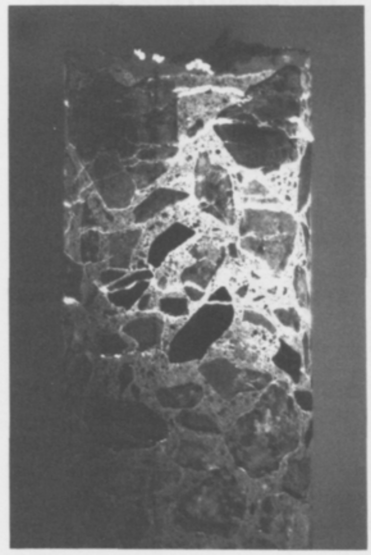
The impact-echo technique for locating voids and delaminations in hardened concrete was developed by Mary Sansalone, first as a graduate student working with Nicholas Carino at the National Institute of Standards and Technology and then as a faculty member at Cornell. With help from William Philpot on computerized image analysis, research associate Kumar Natesaiyer developed an ultraviolet technique for diagnosing the alkali-silica reaction. Natesaiyer also studied an approach to controlling the corrosion of reinforcing steel called cathodic protection, showing that under some circumstances it can cause as many problems as it solves. Graduate students Marcia Simon (now with the Federal Highway Administration) and Richard Jenkins (now at the U.S. Military Acaedemy) developed new methods for assessing the resistance of concrete to freeze-thaw damage and quantified the effect of construction operations on this critical property. This line of research is being continued by a Cornell team sponsored by the American Concrete Pumping Association that is studying the effect of handling on frost resistance. In research sponsored by the American Concrete Institute and private industry, another graduate student, Hani Samaha, evaluated the influence of cracking on the penetration of chloride ions.

Other research is aimed at developing stronger concrete and better construction techniques. These have been the objectives of research conducted by Richard White, Peter Gergely, and Arthur Nilson (who recently retired). While Nilson concentrated on building with stronger, denser, less permeable concrete, White and Gergely have also worked on ways to reinforce or retrofit existing facilities, experimenting with assemblies varying from one-tenth to full scale. Gregory Deierlein has joined this line of research with new ideas about ways to combine structural concrete with structural steel in composite assemblies. Gergely and White are also concerned about designing and retrofitting structures to make them more earthquake resistant—a problem that has been taken more seriously since the San Francisco earthquake of 1989.

Yet other research seeks a deeper understanding of the mechanical and chemical behavior of concrete. Anthony Ingraffea's study of fracture has coupled intricate laboratory work with advanced computer modeling until the distinction between experimental and analytical mechanics has become moot. Meanwhile, James Bisogni has conducted basic work on the chemistry of cement and its interaction with other materials, sometimes with the collaboration of Richard Dick and Leonard Lion.

In the design of most conventional new structures, decisions are made on the basis of generally accepted, simplified models of structural behavior. Such models may not be appropriate, however, when it is necessary to analyze the residual capacity of a marginally deteriorated structure. In such cases, the engineer must turn to more complex represen-

A characteristic greenish-yellow fluorescence coming from cracks in a concrete specimen treated with uranyl acetate is diagnostic of an expansive reaction between the alkalies in Portland cement and amorphous silica in crushed stone (see color photo inside front cover).



Below: Concrete is loaded to failure in Cornell's High-Strength-Concrete Compression Testing Machine, a gift from the family of Samuel Garmezy '13.

Left: The Erie Avenue bridge in Cincinnati, Ohio, remained structurally sound but had to be closed for replacement of concrete decking.

tations of material behavior and structural interaction. To fill this need, John Abel, Anthony Ingraffea, Gregory Deierlein, and William McGuire have been developing a variety of computer-based models that can help assess the capacity of deteriorated facilities.

Getting New Technology to People Who Can Use It

With research taking place on several fronts, progress has been rapid. But new technological developments have to be applied in the field, not in the laboratory. Information must be made available to people involved in the maintenance of transportation infrastructure at all levels, from construction workers to designers and policy makers.

"Information must be made available to people involved in the maintenance of transportation infrastructure. . . ."

Those of us who work with concrete materials in the School of Civil and Environmental Engineering acknowledge a responsibility for technology transfer. This, of course, begins with educating engineers. Constantly changing curricula in both undergraduate and graduate-level courses give students the most up-to-date information and prepare them for developments yet to come.

In addition, we provide training for transportation engineers from around the world. Mary Sansalone has trained engineers from four continents in the use of her new technology, and I have prepared and presented training programs on concrete materials to the departments of transportation in twenty states as well as the Federal Highway Administration and the government of Saudi Arabia. Other faculty members are equally involved, and we believe we are having a genuine impact on the improvement of highways and bridges.

Kenneth C. Hover is a specialist in the deterioration of concrete. After earning bachelor's and master's degrees at the University of Cincinnati, he spent three years as an officer in the U.S. Army Corps of Engineers, became a project manager for a general contractor doing building and bridge construction, and then joined a structural design firm in Cincinnati. Part of his work involved the restoration of seriously deteriorated structures, and he became interested in studying concrete from a materials-science perspective. This led him to further graduate study in the School of Civil and Environmental Engineering at Cornell, where he earned a doctorate and joined the faculty in 1984.

In his research, Hover aims to achieve a better understanding of the fundamental properties of concrete and the way those properties are affected by construction methods and environmental conditions. Several of his research projects combine a materials-science approach with the practicalities of concrete construction and rehabilitation techniques. He received a Presidential Young Investigator award from the National Science Foundation in 1986 and has also won four awards for the quality of his teaching.

BUILDING WINNERS

How the Formula SAE Program Makes Good Cars and Great Engineers

by Albert R. George

When Cornell placed first in the annual SAE formula car competition in Dearborn, Michigan, last May, the twenty-three students who built the winning vehicle were ecstatic. Months of hard work had paid off. But the students were even bigger winners in another way. Their practical experience in designing and building a new car would give them a competitive edge in landing jobs. And the lessons they had learned about teamwork and organizational strategies may help to revitalize the American auto industry.

The Parameters of the Competition

Cornell has been building SAE formula cars since 1986. The annual competition, which is sponsored by the Society of Automotive Engineers (SAE) and patronized by the Big Three auto manufacturers, is the focus of a program that draws the best of Cornell's aspiring automotive engineers. Each year, a team of about twenty students conceives, designs, builds, and refines a car that is evaluated in competition with cars built by students from colleges all over North America.

Every team that participates in the contest develops a small formula racing car that conforms to a set of guidelines intended to insure that all entries are in the same class—and safe to operate. (The power source, for example, must be a four-stroke piston engine with less than 610 cubic centimeters displacement.) Within these guidelines, the students are free to innovate.

The cars are designed to meet a model "customer requirement." A hypothetical manufacturer supposedly wants to market a small, formula racing car for amateur, weekend enthusiasts. The car is to be produced for less than $7,000, although a larger sum may be used to develop the prototype. (The Cornell team has been supported by major gifts from General Motors Corporation.) The students' performance is rated according to a composite, customer-oriented point system that includes cost analysis, design analysis, and technical sales potential as well as aspects of performance such as acceleration, cornering force on a skid pad, maneuverability, endurance, and fuel economy (see box).

Because of this multifaceted scoring system, the car with the highest performance does not necessarily win. A car that is made of exotic materials or depends on complex electronics may not score well in cost analysis. A car that is difficult to manufacture or maintain, or seems relatively unsafe, will not score well in design analysis. Appearance is important for sales presentation. In developing the car, the students must consider proposed innovations from all angles. Just as in industry, they must produce a product that represents the best possible balance between a number of design goals.

The Cornell team evaluates suggested innovations with the computational tools of modern engineering. They are able to simulate, on screen, an approximate analysis of the car driving around the race track upon which the real car will eventually compete. In this environment, they can investigate the effects of a proposed innovation in vehicle dimen-

Formula SAE Scoring System

	Possible Points	*Cornell 1992*
Static events		
Cost analysis	100	52
Design analysis	150	138
Presentation	75	48
Dynamic events		
Acceleration	75	64
Skid pad	50	50
Maneuverability	150	150
Endurance	350	350
Fuel economy	50	3

"lessons . . . about teamwork and organizational strategies may help to revitalize the American auto industry."

The first car that Cornell entered in the SAE formula competition took third place in 1987.

sions, weight, the shifting of gears, the engine horsepower curve, and many other variables. By using this computational prototype, they can see how a change in weight or power would change lap time, for example, and this is then related directly to the scoring system. Thus, they can immediately see how any proposed change would be likely to affect the point structure of the score. Improvements in one area of scoring, such as cornering, can be weighed against a loss of points in another area, such as cost, design, or usefulness in a technical sales presentation.

The History of the Cornell Program

Cornell's participation in the SAE formula competition dates from the fall of 1986, when Jay O'Connell arrived on campus as a transfer student. He had been involved with the SAE formula competition at Brown University, but transferred to Cornell because of our faculty interest in automobile engineering. He soon persuaded nearly a dozen mechanical engineering students to form a Cornell team. The next spring, the car they developed took third place—in a field of about thirty—and Cornell received a "Rookie of the Year" award.

An all-new car built by the 1988 team was lighter, more powerful, and more agile—good enough to win first place. The 1989 car took a respectable third place in a tough field that included vehicles with innovations such as aluminum monocoque frames, fuel injection, turbochargers, and composite materials.

The Cornell team responded with a radically different vehicle in 1990. The design included a powerful fan that evacuated air from underneath the car, sucking it down to the ground. These "active ground effects" gave the car superior handling characteristics; no other car has yet beaten its time around the skid pad. But the fan drew too much power, reducing straight-line acceleration, and the car finished fifth in a field of about forty-five.

The 1991 team planned to continue with active ground effects but give the car more power by using a supercharger. Unfortunately, the SAE decided to outlaw active-ground-effects cars for the sake of safety, and a quick change of plans had to be made. The use of a stressed engine made it possible to build a less massive frame with no loss of strength. The finished car weighed only 475 pounds, and partly modular construction meant that the engine could be replaced quickly and easily. When the engine failed during the endurance race, the modular construction turned out to be a tremendous advantage. But overall, the car only placed twenty-fifth.

The 1992 team decided to have its car ready by February and spend the spring testing it to get all the problems worked out. New innovations were few, but they included turbocharging, a simpler suspension, a fully modular frame, and further savings in weight. The car was tested intensively and its performance proved impressive and consistent. At the contest, which took place in Dearborn from May 15 through 17, Cornell dominated the competition, winning the endurance race, the autocross, and the skid-pad event, as well as awards for outstanding treamwork, best design for safety, best suspension design, and a solid first place overall.

Organizational Lessons

The design of the SAE formula cars is carried out on a nine-month product cycle, which is very short compared with the four- to five-year product cycles that are typical in the automotive industry. A further handicap for the design team is the need to conduct the project with inexperienced personnel; students graduate and move away, and few students remain in the program for more than one year. Nearly everyone has to be "trained on the job" during the product cycle, so incoming students have to be given an almost immediate understanding of the major considerations of automotive engineering, the finances of putting a car together, the time involved in manufacturing it, and the organization required to coordinate the activities of team members working on different parts of the project.

The teamwork involved in building a car for competition gives students a first-hand and practical knowledge of modern engineering and manufacturing concepts. The team is necessarily cross-disciplinary, with different people specializing in various aspects of the operation, from overseeing the finances to developing the suspension system. Most of the students are mechanical engineering majors, but the team also includes people from other disciplines such as electrical engineering and business management.

Early in the year, the students must come to understand the principles of "lean" manufacturing. They must continually bear in mind that the car will be evaluated with a scoring system that simulates customer requirements, albeit in an oversimplified way, and includes points for "customer satisfaction." During the design process, they must also evaluate every option according to the way it could be manufactured and how it is likely to affect the overall point score. This simultaneous attention to design, manufacturing, cost, and customer satisfaction is known as "concurrent engineering."

The author (center) discusses the innovative 1990 entry with A. Marc Breuers '92 (left) and Mark Corigliano '93 (right).

If someone suggests a way to make the car corner better or increase the horsepower of the engine, the team has to figure out what effects this will have on cost and manufacturing time. Could they finish the suggested modification and test it in time for the competition? All students are required to submit, at the end of their affiliation with the project, suggestions on how it could be done better. This is part of an approach to management that is called "continuous improvement."

Over the years, the team has tried various management structures, and there has been a distinct organizational improvement as it moved toward a "flatter" structure. Students with different specialties now work together, rather than as rungs in a decision-making hierarchy. Experience has shown that multiple levels of management tend to impede performance. In the flat approach, decisions are made through group discussion. While this takes more time, it leads to better decisions. Alumni of the team who went on to work on General Motors' Saturn project, which was organized on a flat organizational model, have felt right at home.

Alumni and Industry

Over the years, more than ninety students have been members of the Formula SAE Race Team. Many of these students have gone on, after graduation, to work for automotive companies. Substantial numbers are at General Motors Corporation and Ford Motor Company. Current members of the team keep in contact with these alumni, who often make helpful suggestions.

Many of the program's graduates have become involved in running the SAE Formula competition. Among them are Jay O'Connell and Renee Jameson. O'Connell began work at Ford in the fall of 1988, the year of his graduation. One of his first assignments involved the design of a lighter, less expensive independent rear suspension for the Thunderbird. Ford was not able to implement the idea because of scheduling problems, but people were impressed with the deftness and speed with which the assignment was carried out. O'Connell has subsequently had several other assignments and recently helped to launch the new Mark VIII.

The winning 1992 team grouped for a portrait with their car in Dearborn, Michigan. Back row, left to right: Mark E. Corigliano '93; Antoine C. Pharamond '91, M.Eng. '92; Ashok B. Tripathi '93; A. J. Brohinsky '91 (visiting alumnus); T. Scot Brown '81, MBA '92; James A. Bowen '92; David J. Eagle, '93; Sandor L. Kovacs, '93; Gen R. Sasaki, '94; Kristin L. Holcomb, '92; and Patrick A. Klein, '92. Front row: David N. Spitzer '92 (seated); Benjamin H. Wood '92; Robert S. Busacca '93; Thomas A. Telesca '93; Jonathan E. Jacoby '92; Jason B. Hunter '93; and advisor Albert R. George. Not shown: Matthew W. Atwood '92, Brian J. Callahan '93, David A. Krein '92, Charles D. Walter '93, and Kenneth D. Warnock '92.

Students building a car for the 1993 competition work in the new Automotive Project Facility, which was financed through a grant from General Motors Corporation. The facility is attached to the back of Upson Hall.

Renee Jameson took time off after receiving her Master of Engineering degree in 1989 to attend a high-performance driving school. She then began work at Ford, where she participated in an introductory rotation that included work on the company's active suspension system, a stint in the engine division, a season in the company's patent office, and finishing touches on the ride and handling of the 1993 Mark VIII. Currently, she is assigned to the team that is developing the 1995 Continental.

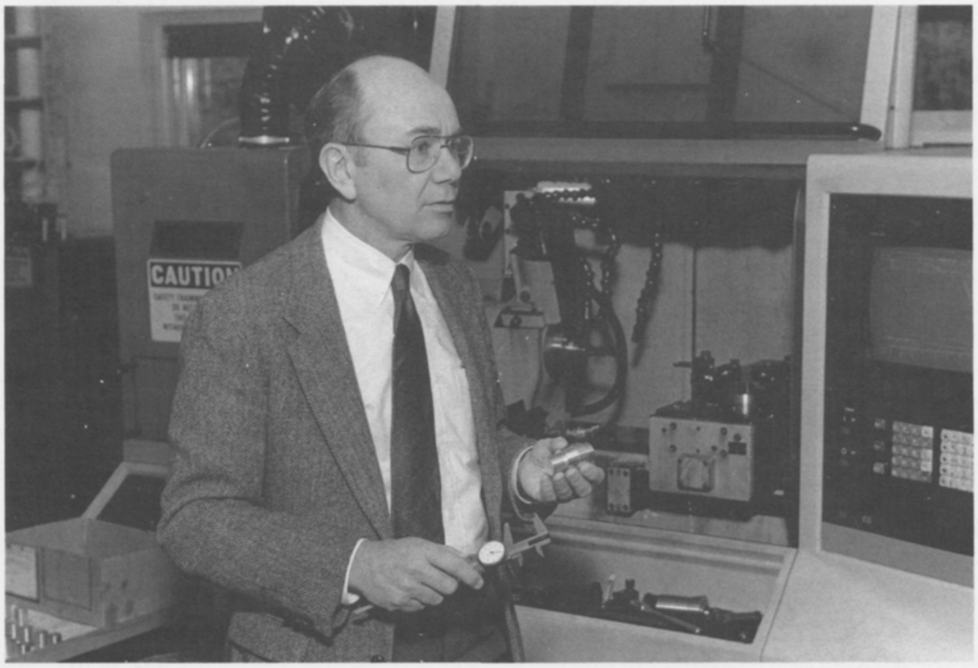
Other graduates of the program work at General Motors. Two at Saturn are Keith C. Mitchell and Patrick A. Hodgins, who both received their bachelor's degrees in 1988 and stayed on for Master of Engineering degrees. Mitchell has worked on the power-train, the optional high-performance engine, and emission certification. Hodgins has worked on reducing noise and vibration and is now concerned with ride and handling for all Saturn models.

In his free time, Mitchell races a Saturn sponsored by the Inner City Youth Valvoline Racing Team in the International Motor Sports Association's Firestone Firehawk events. He ranks highly in the series and also recently became the Sports Car Club of America's national champion in showroom stock Gran Turismo events, driving a Camaro. Hodgins serves as crew chief for the two cars of the Inner City Youth Valvoline Racing Team, which is part of the "Say No to Drugs" program. He also races his own car on weekends when he is not busy with the Inner City Youth team.

The Future of Highway Transportation

Automobiles and trucks are by far the most important mode of transportation in the United States today. Of all the miles traveled by passengers, 81 percent are in automobiles; and shipments by truck account for 78 percent of the money spent for freight. One may argue that public passenger service and rail transportation would be more efficient ways to move people and goods, but the nation depends on road transport at present and will continue to depend on it in the immediate future. Thus, the effectiveness of our highway transportation system, which includes both the roads and the vehicles using them, is extremely important to the well-being of the country.

Recently, the United States automotive industry has been forced to change in order to remain internationally competitive. In order to compete in the modern world, it is necessary to move toward what is called "lean manufacturing." This includes con-



"close simulation of automotive development in the corporate context enables students to appreciate the importance of engineering human systems. . . ."

cepts such as "flat" organizational structure, team-based design and manufacturing, concurrent engineering, design for manufacture, shorter product cycles, and—perhaps most important—design for customer satisfaction.

At the Cornell College of Engineering, we recognize that a knowledge of these and related concepts is important for our graduates, and we have been endeavoring to include them in our programs. One instance is the SAE formula program, whose close simulation of automotive development in the corporate context enables students to appreciate the importance of engineering human systems as well as mechanical devices.

Albert R. George has been a member of the Cornell faculty since 1965, the year after he received his doctorate from Princeton University. His research involves the aerodynamics of both aircraft and ground vehicles, especially mechanisms that produce noise, and he has made substantial contributions to the quest for quieter helicopters. He served as director of the Sibley School of Mechanical and Aerospace Engineering from 1977 through 1987. He is currently director of the Cornell Manufacturing Engineering and Productivity Program (COMEPP), and he was recently appointed to the newly endowed John. F. Carr professorship in mechanical engineering.

In addition to these accomplishments, George has an abiding love for automobiles. He is as comfortable with a dial caliper as with a spreadsheet, and has been faculty advisor to the SAE formula car team since Cornell began participating in the program. He believes that organizational strategy is as important as good design in producing a winning car.

REBIRTH OF THE ELECTRIC CAR

High-Tech Components Give New Life to an Old Idea

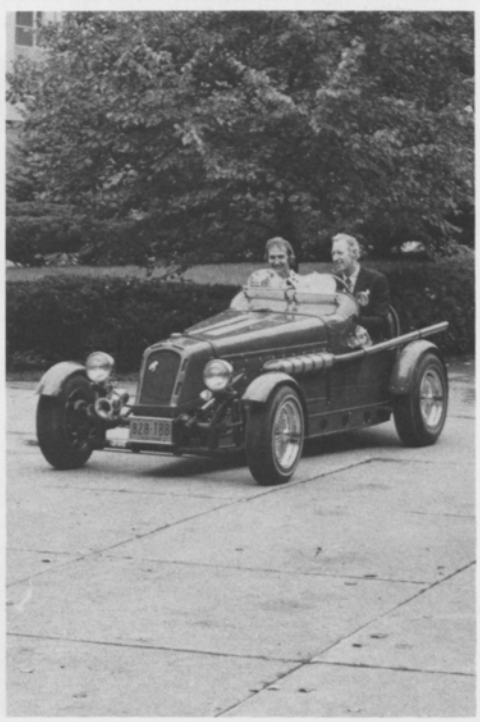
by John Belina

The first automobile to go 60 miles an hour was electric. That was in 1899, when nearly two-fifths of the cars in the United States were electric and it seemed likely that the electric car would be the wave of the future. Electric cars were quiet, durable, and easy to drive. But recharging batteries was slower and more complicated than pumping gas, and by 1930 the internal combustion engine had won the field.

Still, the electric car never quite died; there were attempts to revive it in the late 1940s, and again in the late 1960s and early 1970s. At the School of Electrical Engineering, Joseph Rosson and a team of students began developing an electric car in 1969; three years later a vehicle they designed won the Emissions Award at the North American Urban Vehicle Design Competition. By 1975, the Cornell team was working on its fifth car, which employed a body based on the 1932 Alfa Romeo; it could accelerate from 0 to 40 in 16 seconds and cruise at 60 miles per hour. But the electric car project stalled when the team realized they could not make any more major improvements with the technology then available.

The project was revived, recently, by Robert Thomas, who became interested in new federal incentives to develop alternative fuels while spending a sabbatical leave at the National Science Foundation in Washington. Many technological developments had taken place since the mid-1970s. Structural materials had become lighter and more durable; a.c. motors had become more powerful and compact; batteries had become somewhat smaller and more energy-dense; and electronic components had become smaller and faster. The time was right for a new initiative, which would serve as a training ground for young electrical engineers, and which just might contribute to the development of a truly viable electric car.

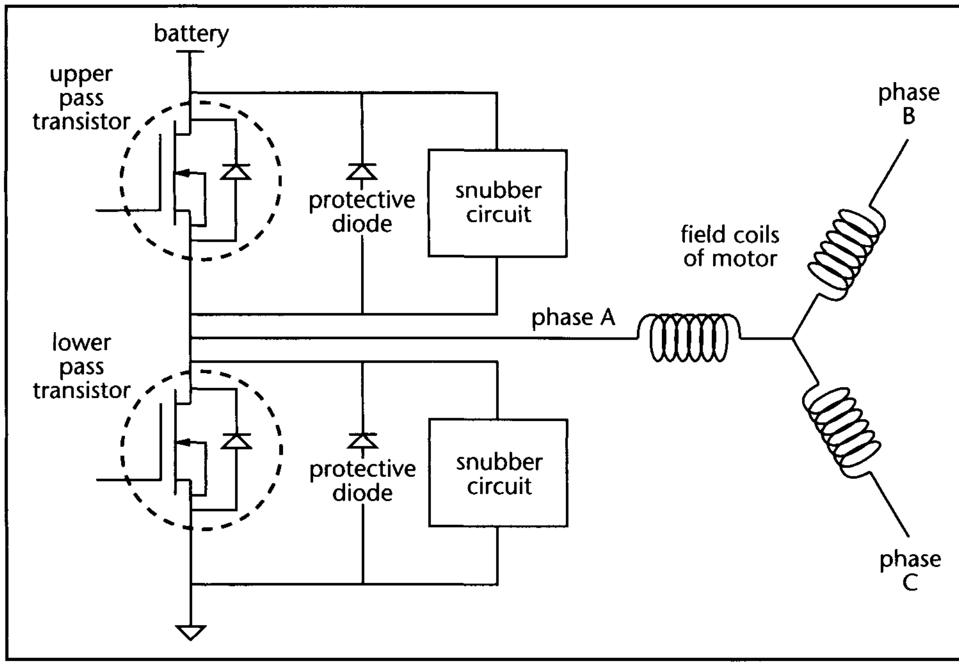
"The time was right for a new initiative, which would serve as a training ground for young electrical engineers. . . ."



Left: Geoffrey Hanshaw '72, M.Eng. '73, and Joseph Rosson with one of Cornell's early electric cars.

Right: Michael Winseck '77, M.Eng. '78, and Cornell's president Frank H. T. Rhodes at the wheel of the 1975 "Alfa."

Figure 1. One of three identical output stages in the electronic controller module. The pass transistors direct current through the motor's three field coils in sequence. The protective diodes and snubber circuits work to absorb transient current spikes and direct them away from the sensitive pass transistors. A large electrolytic capacitor (not shown) is connected between the battery and ground to further reduce voltage transients.



The Decision to Use an a.c. Motor

Since I had been a member of the original team, Thomas recruited me to help coordinate the effort. We got underway during the 1990–91 academic year, with forty-five undergraduate and Master of Engineering students. We are now hard at work on Cornell's sixth electric-powered vehicle. For the body, we are using a small formula car built by students in mechanical engineering. Every year, a group of these students builds a gasoline-powered car to participate in an annual competition (see separate story, page 9), and we are retrofitting the 1990 model with a 15 horsepower (peak), three-phase, a.c. induction motor. This motor has three field coils that must be activated in sequence by alternations in the current. Earlier electric cars built at Cornell all used d.c. motors—an obvious choice, since storage batteries deliver direct current. But motors that run on alternating current can be much lighter and more efficient, justifying a significant increase in motor-control circuitry.

Our power source is four deep-cycle, lead-acid batteries whose weight has been kept to a minimum because they were designed for use in aircraft. The only part of the new electric car that is much the same as in previous efforts, the battery pack delivers 96 volts of direct-current power. One of the project's major challenges is to convert this single d.c. voltage into three-phase, variable frequency, alternating current. To accomplish this, the team is designing a complex power-conditioning unit that uses a new generation of high-voltage, solid-state devices, such as insulated-gate bipolar transistors (IGBTs). By electronically switching connections between the battery pack and the motor, the unit will provide voltage in the correct sequence that emulates the sinusoidally varying voltage produced by an a.c. generator. It must generate three of these voltage wave-forms at once, staggering them by one-third of the duration of a complete wave in order to spin the motor. The resulting composite wave form has square steps, as shown in Figure 2, and will drive our motor, which is optimized for square-wave operation.

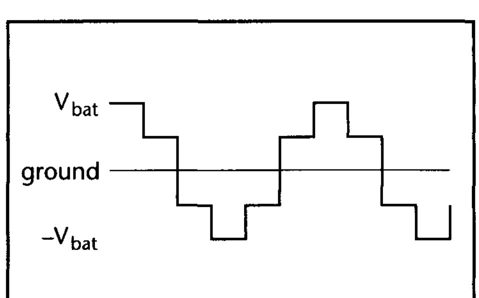


Figure 2. Six-step approximation to a sine wave as presented to the motor coils. The power controller must generate this wave form under a variety of current and frequency conditions.

For this system to work, an unwanted side effect must be dealt with. The interruption of current flowing through a circuit produces a sudden pulse of very high voltage. This effect is put to good use with internal combustion engines, where the interruption of current flowing through a coil produces the spark that jumps the gap in a spark plug to ignite the fuel. But it is a problem for our conditioned-current a.c. motor. The current is continually switched among the motor's three field coils at a rate so great that it exceeds the response times of the electronic components. This means that there are brief instants when one coil has not yet turned off but another is already being switched on, letting a high momentary current flow through the switching transistor and protection diode. The inductive kickback that results when such connections are broken results in sudden voltage spikes. Unless these high-voltage transients are suppressed, they can cause serious damage to the solid-state control elements and the system's computer.

The geometry of interconnections has a significant effect on the generation of voltage spikes at the current levels used in high-power motor systems, and inductive effects in the power-carrying wires themselves need to be eliminated. This is being done, in part, through the development of a new kind of "wire." In addition, several members of the team are working on sophisticated snubber circuits to absorb and rechannel the harmful potentials.

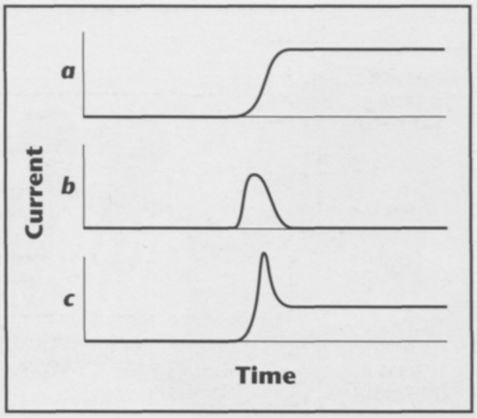
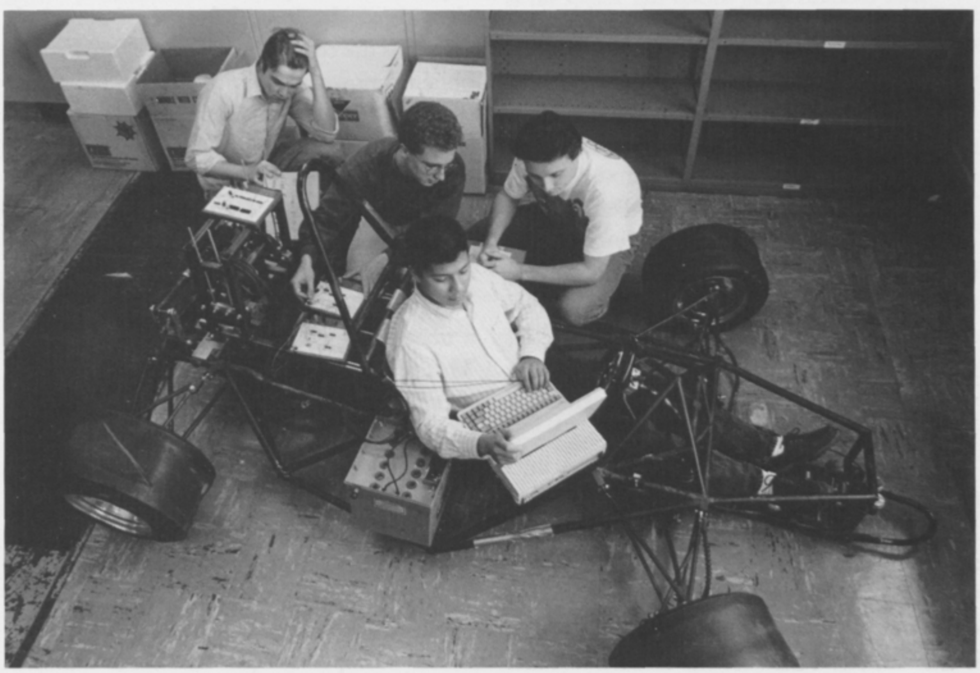


Figure 3. The generation of a voltage spike during a switching transition in the electronic controller module shown in Figure 1. Three wave forms are displayed on a common time axis: a) shows current flowing through the upper pass transistor, b) shows current flowing through the protective diode of the lower pass transistor, and c) shows the current that flows, as a consequence, through the power electronics stage. The momentary voltage transient induced by this surge must be controlled by snubber circuitry and appropriate layout of the components.

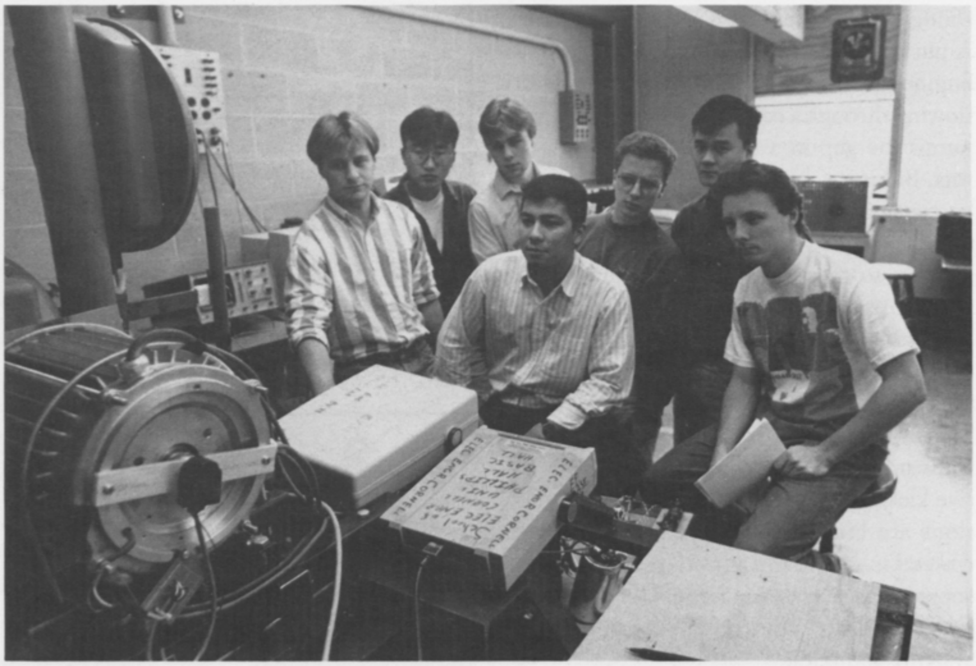
They employ passive devices similar to those used in the surge protectors commonly sold to safeguard computers against unexpected transients in the power grid. Work on the controller, which makes use of the new IGBT technology, should be complete by the end of the current semester.

The Main Challenge: Varying the Frequency

Once these basic problems are taken care of, we have to find ways of varying the frequency of the alternating current. This is what controls the speed of the motor, so the current conditioner must be able to produce, on demand, frequencies ranging from just a few cycles per second (to get the motor started) to



Students check out the computerized control circuits of the electric car currently under construction. Pictured, from left to right, are Jonathan H. Bloedow '94, Andrew Newman '93, Edgar A. Campos '93, and Daniel Dellmyer, M.Eng. '93.



Members of the electric car project monitor the three-phase a.c. motor's response to the control system under a variable mechanical load provided by a dynamometer. Students shown are (left to right): Rich Moakler, M.Eng. '93; James Lim, M.Eng. '93; Jonathan H. Bloedow '94; Edgar A. Campos '93; Andrew Newman '93; Charles Lee, M.Eng. '93; and Daniel Dellmyer, M.Eng. '93.

over 10 kilohertz (to move the motor—and the vehicle—at high speed). At the same time, however, the frequency of the current must be kept from changing so rapidly that the rotor is unable to respond. Only by taking this into consideration is it possible to generate wave forms that will keep the motor operating at its highest torque for a given voltage and optimize the efficency of energy conversion.

A static control system developed last semester allows the motor to operate under a wide variety of fixed speeds and power loads. But real driving conditions seldom involve stable loads; the motor must be able to speed up and slow down, with torque that varies correspondingly. So this semester we are developing and implementing a complex dynamic control algorithm that will enable the vehicle to meet a driver's demands for rapid, yet stable, changes in speed. We have already completed a dynamometer-based testing apparatus that will allow us to evaluate the effectiveness of the control algorithms.

A further feature that must be factored into the overall design is provision for a regenerative braking capability. When the driver of a standard vehicle comes to a fast stop, energy is lost—it just heats up the brakes. But with regenerative braking, which was developed for our earlier electric vehicles, some of this otherwise wasted energy is transferred back into the batteries. This significantly increases efficiency and we calculate that it will increase the vehicle's range by 10 to 30 percent. Thus, we have decided to include it in the design of our new car—even though it adds yet more complexity.

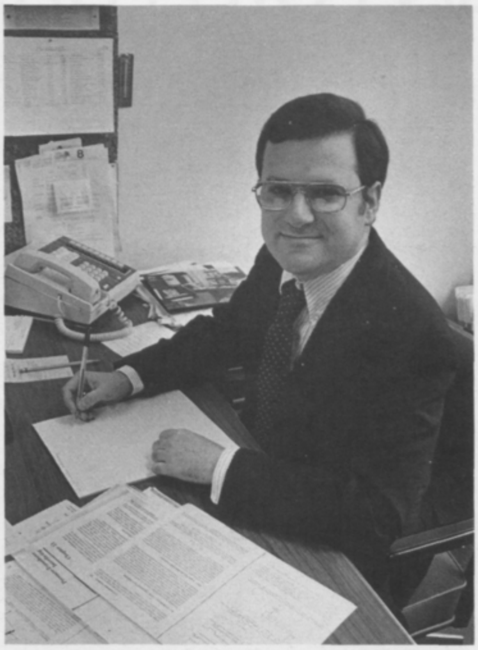
Since the motor depends on the wave forms of the alternating current, and the wave forms depend on the implementation of the control algorithms, the central feature of the whole system is the computer. We were fortunate to obtain a powerful minicontroller, which we acquired through the assistance of Norman Vrana and the generosity of Intel Corporation. This semester, one-third of the students in the project are working to implement the desired control codes on the Intel microcontroller and mount it on the vehicle.

One novel feature of the minicontroller is a fiber-optic interface to the power system. This feature confers an extra degree of protection to the delicate electronics of the minicontroller because the optical mode of transmission allows the minicontroller power supply to be electrically isolated from the source of power for the motor. In addition, optical information transmission lends itself to a token ring communication system between all the major components of the vehicle, which we hope to implement in the future.

Designing an Electric Car,
Training Tomorrow's Engineers

By the end of the current academic year, Cornell's first electric vehicle powered by an a.c. motor will roll off the "assembly line." It will represent the efforts of more than one hundred students in the fields of mechanical and electrical engineering, who have worked on it for three years. They have imagined new modes of operation, simulated innovative designs on powerful workstations, and built prototype, then final, operating systems. In the process, they have learned many important lessons about engineering. Many of the students who worked on the electric-car project under Joseph Rosson now have productive engineering careers, and some members of the new team have already found exciting positions in industry or chosen to deepen their education through graduate study.

By next year, we expect to move the electronics part of the project into newly renovated laboratory space in Phillips Hall, and the mechanical work will take advantage of the new General Motors Automotive Project Facility, which is attached to Upson Hall. Our temporary home in Phillips Hall, this year, was the site of the first digital computer to operate on the Cornell campus. Perhaps it will also play a part in the development of the electric car of the future.



John Belina has been involved with electric cars ever since his student days at Cornell. He worked on electric vehicles built under the leadership of Joseph Rosson while studying for the B.S. and M.Eng. degrees, which he received in 1974 and 1975. He then made a long detour into administration, serving the College of Engineering as director of advising and counseling and as assistant dean for admissions and records. He returned to electrical engineering in 1989, as a lecturer and assistant director of the school. His talents as an educator have been recognized by students selected as Presidential Scholars, and he has been honored with a Dean's Prize, awarded in 1990 for his efforts in advising undergraduates and working with student organizations. He and Robert Thomas share the responsibilities of advising the team of students that is now building a space-age electric car.

"By the end of the current academic year, Cornell's first electric vehicle powered by an a.c. motor will roll off the 'assembly line.'"

DESIGN FOR PEDAL POWER

Building a Human-Powered Commuter Vehicle

by Samuel Landsberger

"In addition to experiencing the joys of the creative process, [students] come to understand the applicability of their analytical course work."

High school students who show an aptitude for science and mathematics are often encouraged to go into engineering. But many of them have never tinkered with a car or taken apart a vacuum cleaner; they may not know what a gear is or how a motor works; and they have little idea of what engineers actually do. Since most of the introductory engineering courses are highly theoretical, such students can progress well into their college careers before they get any hands-on experience with mechanical design or discover the thrill of creating a new device.

The course Mechanical Design and Analysis (M&AE 325) is intended to remedy this situation by giving students with no tinkering experience an intuitive feel for mechanical devices. In the laboratory, they take apart (and hopefully put back together) such common things as a lawn-mower engine, a three-speed bicycle hub, and an electric drill. For some of them, even an electric drill is an exotic implement. But almost everyone has had experience with a bicycle.

The Human-Powered Commuter Vehicle: An Opportunity for Innovative Design

The human-powered commuter vehicle project, which began in the fall of 1989, gives students a chance to develop what is, in effect, a better bicycle. It provides an opportunity for them to work on something whose utility they can immediately appreciate. They research previous efforts in the area, create a design, and build a prototype. In addition to experiencing the joys of the creative process, they come to understand the applicability of their analytical course work. They learn the relevance of structural analysis, strength of materials, fluid mechanics, dynamics and control, heat transfer, and fatigue analysis. And of course they are introduced to mechanisms and components such as bearings and gears, and get practice in speaking with vendors and reading catalogs. Students get the experience of working together, coming up with ideas and evaluating them, working with available materials and processes, testing their ideas in the real world, and writing technical reports—all things that professional engineers have to do.

In my creative design courses, I try to show students how to form a relationship between theory and practice—to glimpse the beautiful synergy that can exist between the two. Students may go on to become highly specialized theorists or efficient pragmatists, but their education as engineers is not complete unless they have some experience of the harmony between spontaneous creation and critical analysis. The role of the designer is to realize this harmony: to free the mind and dream wildly what has never been, and then to contemplate a creation with cool reason and realize what can never be. The result of this positive and negative activity—of life and death processes, as I often refer to them—is the efficient evolution of a novel, useful device.

To flourish as a part of student culture, creative design needs a home as well as a philosophy. A design synthesis studio has been established to serve as a resource center for undergraduate design activity, supporting design-intensive courses as well as independent projects. The synthesis studio is the center of gravity for student design work, providing a place for students to store their hardware, work benches and hand tools for light fabrication of prototypes, a small reference library with texts and vendor catalogues, and a small conference area. In the future, the studio will, hopefully, be enhanced with a few workstations for computer-aided design as well as finite-element and dynamic analysis. These workstations will also enable students to experiment with computer and microprocessor control of their machines.

The Mark I human-powered vehicle was built in 1989–90. The proud designers pictured here are (left to right) Loy C. Y. Kuo '93; Louis J. Algaze '91; Herbert V. Darrow '92; Eric W. Thompson '85; John D. Hwang '91, M.Eng. '92; and Norman R. Prokup '90.

The human-powered vehicle project started with seven students in the fall of 1989. It grew to eleven students in the spring of 1990, and sixteen students in the fall of that year. Since that time, more than forty students have propelled the project forward. Most of the students are undergraduates, although a few Master of Engineering students have also participated. Many participate in the context of the course Design: Beyond the Imaginary (M&AE 425/525), while others get academic credit for their participation through individual design projects. Over the past three years, student energy and commitment have increased as I have realized the importance of letting the students make their own mistakes, gradually relinquishing the role of director and assuming more the role of consultant.

Preliminary Considerations: Objectives and Stability

Design begins with a need. We wanted to create a healthy, practical alternative to the automobile for short commuting and shopping trips—a vehicle that would improve the health of both the driver and the environment, while saving on maintenance costs for both automobile and body. But this idealistic vision had to be boiled down to a set of practical design specifications—a set of initial conditions for the design process. We decided to work toward a vehicle that would be able to transport one person and about 20 kilograms of cargo (two full grocery bags) in reasonable comfort. We wanted a vehicle with a fairing that would protect the rider in inclement weather—necessary year-round in a place like Ithaca. We wanted a vehicle that would remain upright when standing still or skidding on ice. We wanted a vehicle that was light, reasonably fast, and fairly simple to build. How to achieve these goals was what the student design team had to figure out.

The students began by doing research to find out about similar vehicles that had already been invented and to learn what had already been discovered about bicycle dynamics. They did not want to "reinvent the wheel," but to explore new territory. They found HPV News and Human Power (the newsletter and technical journal of the International Human Powered Vehicles Association) especially interesting. They also profited by reading unpublished dissertations on bicycle dynamics.

One of the first decisions that had to be made was how many wheels the vehicle should have. The group considered both four-wheeled and three-wheeled options. The four-wheeled possibilities might have wheels at four corners, like a car, or it might involve two wheels, like a bicycle, with two additional wheels on either side of the rear wheel, to give

The Mark II human-powered vehicle had a triangulated-truss space frame. Among its developers were (left to right) Anthony DeBiase '90, M.Eng. '92; Duane M. Belongie '90, John D. Hwang '91, M.Eng. '92; and Andrew P. Balet, M.Eng. '92. The vehicle had an articulated, crustacean-like fairing, which is shown above.

stability when needed, like the training wheels on children's bicycles. Three-wheeled possibilities involved two wheels in the back, like a standard tricycle, or two wheels in front. All of these options were evaluated in terms of stability, ease of operation, cornering, and ease of construction.

Stable Cornering: Leaning and Steering

We decided early on that we wanted a vehicle with the dynamic cornering stability of a bicycle or motorcycle, which can lean into curves in a way that is only possible for autos when a road is banked. At the same time, we wanted to preserve the low-speed stability of a car; indeed, we wanted a vehicle that would remain upright when stopped. How could this primary goal of both static and dynamic stability be realized?

The problem with the training-wheels approach was that it would require a complex mechanism (or a skilled driver) to put the wheels down at the proper times to provide correct resistance to lean at differing speeds. A vehicle with four wheels disposed in a rectangle would require a differential drive in order to corner properly, as well as constant-velocity joints enabling a leaning rider to power nonleaning wheels, and this would add a great deal in weight and complexity. Standard tricycles are notoriously unstable during braking; they can decelerate far faster than they accelerate, and if the front wheel is turned slightly, they flip right over. (All-terrain vehicles have been outlawed or restricted in many places because of their propensity to overturn on their drivers.) This process of elimination left us with the tricycle that has two wheels in front and the problem of how to couple leaning and steering.

Thinking about this problem led the students into a serious consideration of what actually happens when a bicycle goes around a corner. Normally, one leans into a curve, but if the tricycle were designed to permit an unrestrained lean in any direction, the rider might end up leaning in the wrong direction under the influence of centrifugal force, with disastrous results. Therefore, the students decided to mechanically couple the leaning and steering actions so that the rider can only lean *into* a turn. This ensures cornering stability and gives the lean-into-the-turn feel of a two-wheeler without sacrificing static stability. Instead of handle bars or a steering wheel, the rider grips rigid handles in both hands and controls the direction of the vehicle by leaning from side to side. The tilting of the central spine on which the rider is seated actuates tie rods that change the orientation of the wheels.

A weakness in the design is the tendency of the paired wheels to shimmy at speeds over 15 miles per hour. We have controlled this, however, by means of a spring-damper system that alters the resonant frequency of the vibrations while removing energy from any oscillations that may occur. The analysis and correction of this self-induced vibration has been a good experience for juniors who have just completed M&AE 326, Dynamics and Control.

Most people find it easy to learn to ride the lean-to-steer vehicle; team members "test marketed" it in front of Willard Straight Hall one sunny day in the fall of 1991 by letting passers-by take it for a spin. By and large, the students who tried out the prototype commuter vehicle liked the intuitive way it handled, although many of them observed that it ought to have a reverse gear.

The Evolution of a Design: Simplicity vs. Complexity

So far, the students have built three consecutive models. Mark I was a relatively simple vehicle whose backbone structure consisted of a large steel tube with an attached seat. It was designed as a rough proof-of-concept prototype, to test the lean-to-steer idea, and was quite heavy.

The Mark II vehicle had a triangulated-truss space frame, and several students became skilled welders while putting it together. It was elegant and reasonably light—a finite-element mesh brought to life—although difficult to manufacture. It had a beautiful and safe fairing that consisted of three articulating segments made of Lexan plastic, which was donated by General Electric Company. Unfortunately, however, the fairing was so heavy that once the vehicle leaned it was difficult to right it.

The Mark III was a simpler and leaner machine, representing a partial return to Mark I. It was built on a single backbone, but more optimally sized and with a better lean-to-steer mechanism. In addition, it had an elegant, lightweight tent-like fairing that could be opened and closed with a zipper.

Throughout the project, students have learned the importance of social skills and values in the design process. In addition to the give-and-take of working as a team, they have found that design is part of a historical continuum. Building the Mark I required students to exercise restraint and self-sacrifice, for they would have preferred to end up with a beautiful, shiny finished product. But what they had to do, given the time constraints of student life, was demonstrate an idea that future students would refine. Subsequently, students have had to learn how to harvest the fruits of earlier efforts and experience design as a continuous evolution involving creative (and hopefully beneficial) mutation.

Looking Ahead to Cleaner, Healthier Commuting

In 1991 the Mark II vehicle was entered in the Versatile Vehicle Division of the Ninth International Human Powered Vehicle Competition held in Milwaukee, Wisconsin. It was judged according to a range of

Further improvements resulted in the Mark III human-powered vehicle, exhibited by (left to right) David H.-Y. Liu '93, Joshua T. Wang '92, Mark K. Tyson '93, Raj Sundra '90, Timothy P. Beaton '93, Bhavesh M. Upadhyaya '93, David M. Russell '93, and Eric E. Dirnbach '92.

parameters, such as comfort, load capacity, stability, and speed. In overall performance, it placed ninth out of twenty-one entrants. Although not as fast as two-wheeled contenders optimized for the scoring formula, in spirit and performance it was one of the more interesting creations. The judges were quite impressed with the novel but intuitive lean-to-steer mechanism and this earned us several points for originality.

"the judges were quite impressed with the novel but intuitive lean-to-steer mechanism. . . ."

The Mark III vehicle cruises comfortably at 15 miles per hour on the level, and is capable of going up Buffalo Street hill at a crawl. There are a few wrinkles yet to be ironed out, however. The vehicle is hard to steer at low speeds, and the impact of rocks and potholes is jarring. So this year, students are working on a novel steering system that incorporates a steering wheel for use at low speeds as well as the lean-to-steer mechanism. They are also developing a lightweight suspension system, the reverse gear that potential customers have asked for, and a compact "zero-max" variable gear reduction that will allow alternative propulsion by a small, high r.p.m. electric motor.

Continued work may produce a practical vehicle that bridges the gap between a bicycle and a car. It could be used in many places where existing traffic is slow or where there is a good system of bicycle paths. Medical authorities are continually advising people that they need more exercise to maintain good health, and getting to work in a human-powered vehicle is environmentally much sounder than using one that depends on fossil fuel. As metropolitan areas take more serious measures to reduce pollution, strange-looking human-powered vehicles may become quite common.

Samuel E. Landsberger is committed to fostering helpful technologies. His technical interests include creative mechanical design, kinematics, and robotics. In addition to human-powered commuter vehicles, his student projects include underwater robots to study pollution and gather data from the marine environment; accurate, high-speed, force-reflecting, parallel-link manipulators; appropriate technology for low-income people; and the design of low-cost devices to assist the elderly and the handicapped.

An assistant professor in the Sibley School of Mechanical and Aerospace Engineering, Landsberger earned his doctorate at the Massachusetts Institute of Technology in 1988 and joined the Cornell faculty in 1989. His enthusiasm for teaching mechanical design to undergraduates won him a 1991 Dean's Prize for Excellence and Innovation in Teaching.

VEHICLES, GOODS, AND DATA

Managing Information for Efficient Transportation

by Mark A. Turnquist

What happens if you send a truck full of bananas to Boise and no one is there to unload it? This is not a trivial concern. When freight moves between shipper and receiver, it often uses two or three different modes of transportation. The bananas may arrive by boat, get transferred to a train, and ultimately be distributed by truck. Each time they are transshipped there is a potential for delay, which diminishes the efficiency of the operation as well as the salability of the bananas.

Different modes of transportation have developed separately, with coordination between them left to the people who use their services—or to middlemen such as shippers' agents and brokers. Thus, while maritime shipping, railroads, and trucking may be prompt and efficient, the interfaces between them are weak points in the overall network. In an intermodal rail yard, for example, truck and train operations must be coordinated. If trucks are assembled too early, they and their drivers sit idle while waiting for the train. Conversely, if they are too late, the freight cars sit idle while waiting to be unloaded.

Such problems can be minimized by viewing the freight transportation system as a seamless whole and using modern computer technology to track both freight and vehicles. This approach, which I have been helping to develop, was endorsed by Congress late last year. The Intermodal Surface Transportation Efficiency Act of 1991 presents a new vision of the nation's transportation system—a concept in which autos, buses, trucks, trains, and planes form an integrated, closely coordinated system that will provide smooth, multimodal service for both passengers and freight.

Coordination, Responsiveness, and Resource Utilization

Total quality management for the movement of freight requires an emphasis on the whole system with constant attention to the customer. Safety and reliability should not be sacrificed, but it is necessary to improve coordination, responsiveness, and resource utilization to provide more effective service.

In an operational sense, coordination is the goal of bringing all the required pieces together in the right place at the right time. In a container port, for example, this means having gantry cranes, trucks or rail cars, and people available on the dock when a ship is ready to be unloaded. Equally important is the availability of the required information about each container—contents, customs clearance, liability to tariffs, and destination.

Improved responsiveness means being able to meet changing demands quickly and effectively. As markets shift from one place to another or changes in the price of commodities bring about changes in the location of suppliers, the system must be able to adapt delivery schedules or capacity requirements to meet new needs.

One way to satisfy the responsiveness objective is to provide excess capacity, with a surplus of equipment and facilities sufficient to accommodate any demand that may arise. But this leads to poor resource utilization and increased total cost. Hence, it is better to advance the responsiveness-utilization frontier, as shown in Figure 1. The goal is to move from

"while maritime shipping, railroads, and trucking may be prompt and efficient, the interfaces between them are weak points in the overall network."

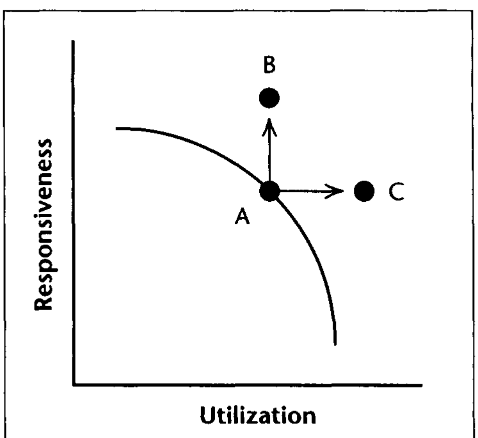


Figure 1. The responsiveness-utilization frontier. It is possible to improve on a given combination of responsiveness and utilization (A) by increasing either responsiveness (B) or utilization (C), so long as neither is sacrificed in the interests of the other.

an operating point with a given combination of responsiveness and utilization to a new operating point where one objective is advanced without sacrificing the other, or where both are advanced simultaneously.

The most promising way to push out the responsiveness-utilization frontier, achieving simultaneous improvement in both objectives, is to collect and use more accurate and up-to-date information about system status and projected future events. Real-time planning requires real-time data about present status and reasonable projections of future needs. Thus, an ability to collect, organize, move, and use data more effectively is vital to the success of the endeavor.

A Comprehensive Framework for Systemic Improvement

To improve coordination, responsiveness, and resource utilization, it is helpful to think in terms of relations between related flows of goods, physical resources, and information. Each of these three elements moves in its own network, as shown in Figure 2. Goods move from vehicle to dock to vehicle on their way from origin to destination; trucks or rail cars move from shipment to shipment as they are used and reused; and information moves from computer to computer (or person to person) through its own channels. These three networks can be treated as layers in a larger network, with connections among the layers. In the example of a container port, unloading cannot begin until the ship with the containers, the crane, and the trucks or rail cars are all present—and information about the shipment has also arrived, been assembled, and distributed to the appropriate people.

The representation of freight transportation as an interconnected flow of goods, resources, and information emphasizes one of the major sources of delay. Delay occurs when the layers are not tightly connected, so that one or more of the elements required for a processing step is not present when needed. Delay may also occur during a transportation phase, but delay during a processing step is easier to remedy.

To see how analysis in terms of related levels of flow can help push out the responsiveness-utilization frontier, consider a transfer process in an intermodal rail yard. Trains carrying containers arrive and are served by unloaders, which pick up the containers and place them on truck chassis. The process as a whole can be modeled as a queuing system, in which the "customers" are the containers and the "servers" are the loaders. If no truck chassis are available, the servers stop operating (or are forced to stack containers on the ground, from which they must be retrieved later). The

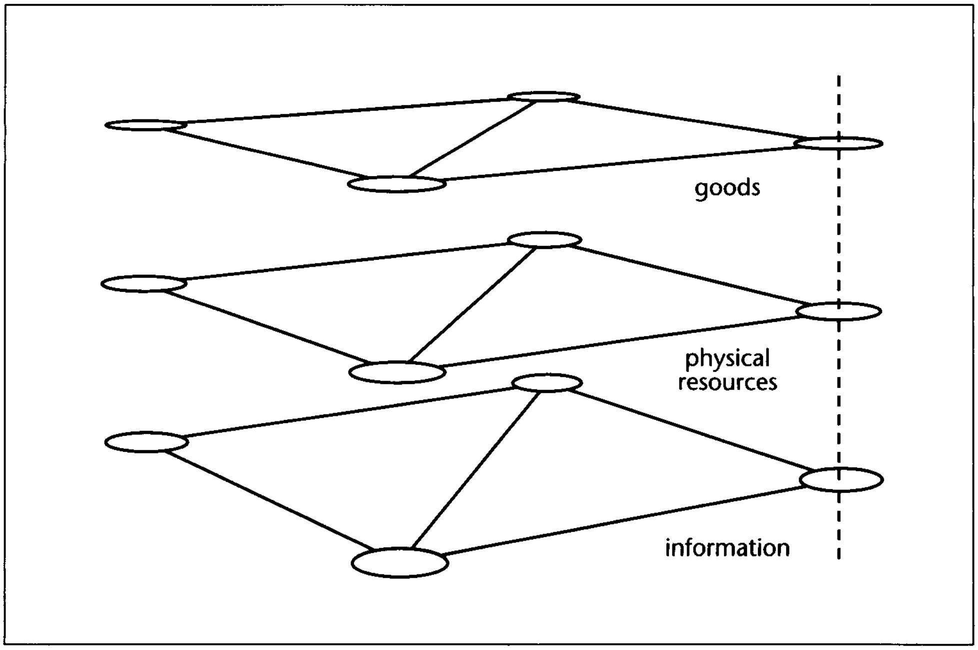


Figure 2. The relationship between structural levels in the freight transportation network. Goods, physical resources (including vehicles), and data form discrete but interconnected systems. For a given action to occur, elements from all three levels must be in the same place at the same time.

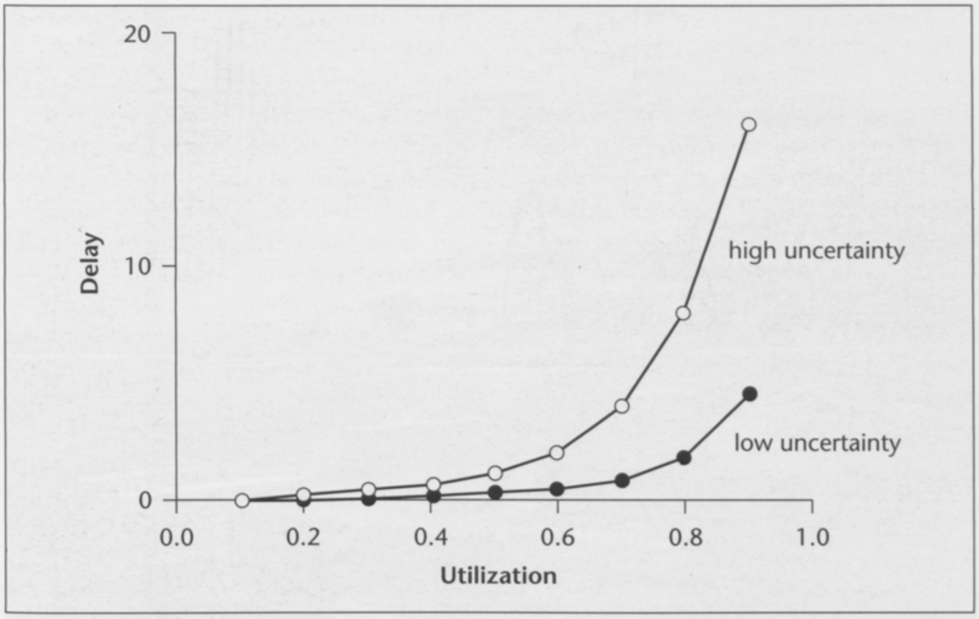


Figure 3. Delay versus utilization in loading containers. Delay is measured as a multiple of the mean processing time for a container. Utilization is measured as the ratio of the average arrival rate to the average service rate. In the curve marked "high uncertainty," interarrival and processing times are random. In the curve marked "low uncertainty," the standard deviation of both interarrival times and processing times has been reduced by 50 percent.

time between the arrival of successive trucks may be somewhat random, and the process of unloading and loading may have a random duration for each container. The randomness of these times reflects a lack of information and coordination.

The value of additional information is illustrated in Figure 3, which shows the relationship between average delay time for arriving containers (roughly speaking, the inverse of responsiveness) and degree of utilization of servers under two different degrees of uncertainty. For the curve labeled "High Uncertainty," the time between the arrival of containers and the service time are both highly variable. The other curve, marked "Low Uncertainty," represents a 50 percent reduction in the variability of both times. More information about the system results in both a higher utilization of resources and a reduc-

In an intermodal terminal, freight containers are transferred from railroad cars to trucks.

At a container port, gantry cranes provide the interface between freight transportation on land and ocean.

tion in delays—which is equivalent to an increase in responsiveness. In other words, additional information has made it possible to push out the frontier of the responsiveness-utilization tradeoff.

Scheduling Equipment to Increase Efficiency

Another, related way to use information to improve coordination, responsiveness, and resource utilization involves scheduling the movement of vehicles in a widely distributed network. Railroads, for example, have to reposition empty freight cars for reloading. Customers typically request a certain number of cars with specified physical, mechanical, and economic characteristics, and set a time window within which they will be needed. The railroad then faces the task of matching available equipment with this order, and moving cars from many different locations to the shipper's venue within the desired time window.

This operation can be carried out more effectively by using information to become proactive, rather than reactive. Empty cars must often be dispatched to likely loading points before an order is received, based on forecasts of demand. These movements must be coordinated across the entire network, over a planning horizon of one to two weeks, in order to make effective use of the vehicle assets owned by the railroad.

In order to address this problem, my colleagues and I have developed a modeling approach based on sophisticated network optimization methods that provides realistic and feasible short-term (fourteen-day) distribution strategies based on freight-car supply and demand as well as network cost functions. The network optimization determines the flows of empty freight cars between various origins and destinations, over time.

The results of this optimization can then be translated into specific car-movement orders which guide the day-to-day operation of the car-management process. Models of this type have been implemented at CSX Transportation, a major railroad covering the eastern United States, and at Union Pacific Railroad, which covers much of the West.

Trends in Manufacturing and the Movement of Freight

The success of manufacturing and retailing strategies that are currently under development will depend, to a large extent, on the efficiency of freight transportation. One instance is just-in-time (JIT) production systems, which aim to minimize waste and the cost of maintaining large inventories by scheduling the acquisition of raw materials so that they arrive just as they are needed in the manufacturing process. Another new strategy is the "Manufacturing 21" concept, which is being developed in Japan. It involves the manufacture of made-to-order finished goods at locations near final demand. Chains of facilities stretching across the globe would take advantage of regional variations in the availability of raw materials, labor, demand, and other variables so as to minimize cost and maximize customer satisfaction. Both JIT and distributed manufacturing clearly require transportation services that operate smoothly and predictably.

My colleagues Arnim Meyburg, Linda Nozick, and Richard Schuler are also investigating various means to improve the performance of transportation systems. Initiatives include efforts to improve resource utilization in the private sector as well as efforts to identify public policies that will enhance the economic benefits of transportation, both regionally and nationally.

In order to create a seamless intermodal freight transportation system, it will be necessary to focus as much attention on moving and managing data as on moving goods and vehicles. The use of real-time data will make it possible to move freight between increasingly diverse origins and destinations, while providing better service to customers and utilizing resources more efficiently.

The explosion in speed and capacity of computing hardware over the last decade opens up dramatic opportunities for the improvement of transportation systems. The critical challenges are to ensure that the right data are in the right place at the right time and to educate managers who will be able to take advantage of these data. With an ongoing research program in transportation systems and an Engineering Management option in the Master of Engineering program, Cornell's College of Engineering is doing its part.

Mark A. Turnquist is a professor in the School of Civil and Environmental Engineering. His current research focuses on management of large complex systems in which uncertainty plays a major role. Many applications involve transportation, but some of the research is aimed at manufacturing logistics.

Turnquist earned the Ph.D. in 1975 at the Massachusetts Institute of Technology, where he specialized in transportation systems. During a four-year affiliation with Northwestern University, he was honored for his outstanding teaching. Since coming to Cornell in 1979, he has taught courses in transportation systems analysis and more recently in risk analysis and engineering management. He has also served as a consultant to public agencies and carriers in the transportation industries and to manufacturing companies.

"it will be necessary to focus as much attention on moving and managing data as on moving goods and vehicles."

Mary Sansalone, associate professor of civil and environmental engineering, has been named Professor of the Year by the Council for Advancement and Support of Education. At right, Sansalone works with Ed Hoffler '93 (left) and Devang Shah '94 on balsa wood bridges that her students design in an introductory structural engineering course.

■ ***Mary J. Sansalone***, associate professor of civil and environmental engineering, was named Professor of the Year by the Council for Advancement and Support of Education.

"It is a particular pleasure for CASE to recognize Mary Sansalone for sharing her enthusiasm for her profession with her students and for providing them with the encouragement to develop the skills necessary for their academic and non-academic success," said CASE President Peter McE. Buchanan. "She is an inspirational educator and a superb scholar."

The award includes a cash prize of $10,000 and the opportunity to lecture at the Smithsonian Institution. The recipient is selected by a panel of judges, including a student, a past CASE award winner, a community college president, and three education experts.

According to William B. Streett, dean of the College of Engineering, Mary Sansalone has created new undergraduate and graduate courses that have been extraordinarily successful. She has devised effective ways to reach out to students who need extra help to succeed. Under her leadership the student chapter of the ASCE won the "Best Chapter of the Year" award last year. She won the Tau Beta Pi award—the top teaching award in the college—in her second year on the faculty, and she has won four other awards at Cornell for excellence and innovation in teaching.

In addition to her record and reputation as an outstanding teacher, Sansalone has won a Presidential Young Investigator Award from the National Science Foundation for her research, and in 1990 she was awarded the Wason Medal by the American Concrete Institute for the best paper published that year in her field of scholarship.

Sansalone earned the B.S. in civil and environmental engineering from the University of Cincinnati in 1982 and the M.S. and Ph.D. degrees in structural engineering from Cornell University in 1984 and 1986. She spent one year with the National Institute of Standards and Technology, then joined the Cornell faculty in 1987.

The CASE Professor of the Year competition was established in 1981 to recognize faculty members for extraordinary commitment to undergraduate teaching, for contributions to the lives and careers of students, and for service to their institutions and the teaching profession. Sansalone is the first engineering professor, the first member of the Cornell faculty, the first person from an Ivy League university, and the youngest person to win this prestigious award.

■ Five new faculty members joined the College of Engineering in fall 1992.

Alexander L. Gaeta has joined the faculty in the School of Applied and Engineering Physics. His research involves the dynamical and quantum-statistical properties of light generated by nonlinear optical processes. Other areas of interest include instabilities and deterministic chaos in nonlinear optical interactions and the development of new nonlinear optical techniques for generating ultra-short laser pulses. Gaeta earned the B.S. (1983), M.S. (1985), and Ph.D. (1990) in engineering physics at the University of Rochester. A member of the Optical Society of America, Gaeta worked for two years as a postdoctoral research associate at Rochester before joining the Cornell faulty.

Linda K. Nozick is a member of the faculty in the School of Civil and Environmental Engineering. Her research focuses on understanding how systems work and what can be done to improve their performance. Systems of particular interest are transportation and manufacturing. She is currently developing a user-friendly prototype of a decision support system for providers of intermodal rail-truck service. She also teaches courses in engineering management methods and decision making. Nozick earned the bachelor's degree (1989) in systems analysis and engineering at George Washington University and the master's (1990) and Ph.D. (1992) in systems engineering at the University of Pennsylvania.

Alfred Phillips, Jr., has joined the faculty of the School of Electrical Engineering. His research interests include quantum mechanical devices, process modeling, and epitaxial reactor modeling. Phillips, whose degrees are in physics, worked for two years at the Goddard Space Flight Center, then began a 24-year career with IBM. He first came to Cornell in fall 1991 as an IBM faculty loan fellow working with the College of Engineering Office of Minority Programs. An active member of the Institute of Electrical and Electronics Engineers, Phillips received the IEEE Centennial Award. He holds seven U.S. patents and has received three IBM patent awards. He earned the B.S. degree in 1961 from Loyola University at Chicago and the M.S. and Ph.D. degrees from Howard University in 1963 and 1968.

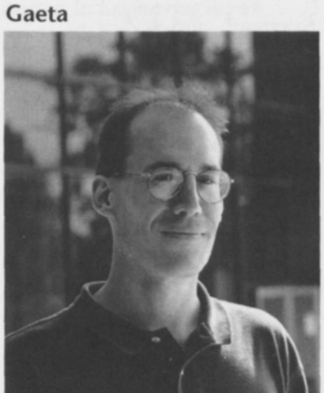
Ronitt A. Rubinfeld has joined the faculty in the Department of Computer Science. Her primary research interests are program result checking, randomized algorithms, computational complexity, and cryptography. She was a visiting research fellow in 1991–92 at the Hebrew University in Jerusalem, and in 1990–91 at Princeton University. Rubinfeld earned the bachelor's degree in computer engineering at the University of Michigan in 1985 and the doctorate in computer science at the University of California at Berkeley in 1990.

Elizabeth H. Slate is a member of the faculty in the School of Operations Research and Industrial Engineering. Her current research interests include parameterizations for natural exponential families with quadratic variance functions and third-derivative summaries as parameterization diagnostics. Prior to joining the Cornell faculty, Slate was a research scientist at Carnegie Mellon University where she taught a statistics course for undergraduate engineering and science majors and conducted research in quality control. She also spent a summer as an intern with the statistics group at Alcoa Research Laboratories in Pennsylvania. Slate earned her degrees at Carnegie Mellon, completing the B.S. in applied mathematics and computer science in 1986 and the M.S. and Ph.D. in statistics in 1988 and 1991.

Rubinfeld

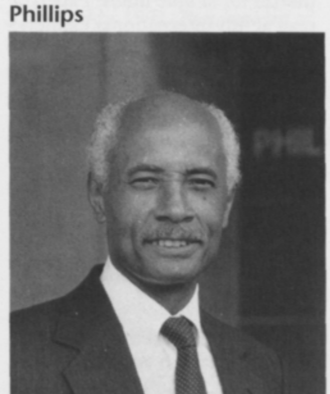
Slate

Gaeta



Nozick

Phillips



Current research activities in the Cornell College of Engineering are represented by the following publications and conference papers that appeared or were presented during the three-month period April through June 1992. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

AGRICULTURAL AND BIOLOGICAL ENGINEERING

Albright, L. D., N. Adre, and *A. Rousseau.* 1992. System characteristic graphs as a basis for ventilation system control. Paper read at Summer Meeting, American Society of Agricultural Engineers, 21–24 June 1992, in Charlotte, NC.

Bell, J. L., and *T. S. Steenhuis.* 1992. Fast and far-reaching flow in soil. Paper read at USDA Agricultural Research Service Symposium 17: Agricultural Water Quality Priorities, 4–8 May 1992, in Beltsville, MD.

Derksen, R. C., R. C. DeMond, K. M. Switzer, and *M. C. Jorgensen.* 1992. Spray containment and automatic recovery system for vineyards. Paper read at Summer Meeting, American Society of Agricultural Engineers, 21–24 June 1992, in Charlotte, NC.

Muck, R. E., and *R. E. Pitt.* 1992. Aerobic losses at the silo face. Paper read at Summer Meeting, American Society of Agricultural Engineers, 21–24 June 1992, in Charlotte, NC.

Pivetz, B. E., J. W. Kelsey, T. S. Steenhuis, and *M. Alexander.* 1992. (Bacterial) life in the fast lane. Paper read at USDA Agricultural Research Service Symposium 17: Agricultural Water Quality Priorities, 4–8 May 1992, in Beltsville, MD.

Rotz, C. A., *R. E. Pitt,* R. E. Muck, M. S. Allen, and D. R. Buckmaster. 1992. Economics of direct cut harvest and storage of alfalfa silage. Paper read at Summer Meeting, American Society of Agricultural Engineers, 21–24 June 1992, in Charlotte, NC.

Shalit, G., T. S. Steenhuis, J. Boll, L. D. Geohring, H. A. M. Hakvoort, and *H. M. van Es.* 1992*a*. Agricultural tile lines for sampling tillage practices in soils with preferential flow paths. Paper read at 17th General Assembly, European Geophysical Society, 6–10 April 1992, in Edinburgh, Scotland.

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Balbuena, P. B., D. Berry, and *K. E. Gubbins.* 1992. Theoretical interpretation and classification of adsorption isotherms and solvation forces for simple fluids. Paper read at International Symposium on Fractal and Physically Adsorbed Molecular States, 14–15 May 1992, in Chiba, Japan.

Balbuena, P. B., C. Lastoskie, *K. E. Gubbins,* and *N. Quirke.* 1992. Theoretical interpretation and classification of adsorption isotherms for simple fluids. Paper read at 4th International Conference on Fundamentals of Adsorption, 17–22 May 1992, in Kyoto, Japan.

Cohen, M. R., and *R. P. Merrill.* (1990). Adsorption of pyridine on Ni(111): A high-resolution electron energy loss spectroscopy, angular-resolved UV photoemission, and x-ray photoelectron spectroscopy study. *Langmuir* 6:1282–88.

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Cracknell, R. F., and *K. E. Gubbins.* 1992*a*. Molecular simulation of adsorption and diffusion in VPI-5. Paper read at International Symposium on Fractal and Physically Adsorbed Molecular States, 14–15 May 1992, in Chiba, Japan.

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Editor:

In the last issue of the *Cornell Engineering Quarterly* you asked for comments on the presentation of the material. I must confess that the articles are much too technical for me to follow. They read like technical dissertations written by research scientists, which, of course, they are.

Your magazine is called "Cornell *Engineering*," but I can't recall the last time I read something pertaining to Engineering. I am concerned about the trend to make Cornell a research oriented institution. We are getting further and further away from an Engineering College.

To quote from your article: "Faculty members who are used to writing for scholarly journals sometimes find it difficult to address a more popular audience." I pity the poor students! How do such faculty members teach *Engineering*? They would be lost in industry where one is constantly trying to sell a project or explain technical matters to nontechnical management or financial personnel.

Frederick G. Miller, '35
Chatham, Massachusetts

Editor:

I, for one, prefer the 8-1/2"x11" format of the *Cornell Engineering Quarterly.*

Concerning the level of presentation, I prefer the high level currently used. So much of the media, in trying to make things accessible, have left the intelligent reader starving for more. The higher level distinguishes the *CEQ* from more simplistic science publications. Please continue to stretch our horizons.

John H. Stuart, '89
Fairfax, Virginia

Editor:

1) I think I preferred the earlier design of the magazine since I was so used to it.... However, given the fact that the new design is in place, it probably makes no sense to revert to the original design.

2) Please do not change the level of the articles. I firmly believe that the faculty are doing an outstanding job in relaying their ideas to specialists trained in other areas. I find all of the articles accessible and interesting.

Edl Schamiloglu, Ph.D. '88
Assistant Professor, Electrical and Computer Engineering
University of New Mexico
Albuquerque, New Mexico

Editor:

Your magazine is excellent. A compromise on authors would be OK, but please continue at the high level. If staff can write at the same high level, staff authorship would not be a letdown.

E. C. McIrvine, Ph.D. '59
Consultant, R&D Management
Pittsford, New York

Editor:

I can offer my opinion as a nonengineering regular reader (my field is languages and linguistics). When my husband [Professor William L. Maxwell, Operations Research and Industrial Engineering] brings home the *Quarterly,* I always read it all—partly because it is his field, partly to keep up to date with technical advances, partly to see specifically what Cornell is doing, and partly because, as in the last issue, some of the articles are in the area of environmental studies, which is the field of our undergraduate daughter. I do not find the articles too technical and I can understand them. I see no need for any significant change.

Judith B. Maxwell
Ithaca, New York

Editor:

I suggest that you retain the present focus on articles written by faculty and technical staff. However, you might want to have an occasional article written by you or another professional writer. This could be on some unusually complex area or issue where a vantage point from a skilled writer who is not an expert might help to make a subject accessible to a broader group of readers.

Another approach that might prove popular would be to have an occasional interview, where you could draw out reactions to your own questions. Such interviews could be either on technical subjects or on educational issues, priorities, trends, and developments. It would familiarize readers with the human side of the college and the many personalities that make Cornell such an interesting and stimulating place.

Richard N. White
Professor, Civil and Environmental Engineering
Cornell University
Ithaca, New York

Erratum: Due to a printer's error, the photograph on page 13 of the summer issue was inverted. Consequently, the coordinated movement referred to in the caption actually appears in the lower right.

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