NANOTECHNOLOGY AND ITS POTENTIAL IMPACT ON TRANSPORTATION

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In 1959 one of the nation's top physicists, Richard Feynman, astounded his colleagues by proposing that "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom." Like most scientists at the time, Feynman's contemporaries doubted that it would ever be possible to actually manipulate atoms. Today, however, "nanotechnology" is yielding atomic- or molecular-scale components in everything from hard disks to coatings—resulting in sales totaling tens of billions of dollars a year (see Science, February 20, 1998). What will be the impact of this revolutionary technology on transportation?

Background

> **"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."**
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> **Neal Lane**
> **Assistant to the President for Science and Technology, 1998, Testifying before Congress as Director of the National Science Foundation**

Put simply, "nanotechnology" is the building of devices and materials at the level of atoms and molecules and the exploitation of the novel properties and phenomena at that scale. It gets it name from "nanometer," the unit of measurement representing one-billionth of a meter, or about ten times the size of an individual atom. (In comparison, microtechnology is at the level of microns — a millionth of a meter — gargantuan by the standards of nanotechnology.) Ten nanometers are 1,000 times smaller than a human hair's diameter; there are as many nanometers in an inch as there are inches in 400 miles. The term "nanotechnology" generally refers to work done at the scale below 100 nanometers.

While in 1959 researchers were skeptical of the feasibility of manipulating atoms, today technologies such as scanning tunneling microscopes let scientists "see" individual atoms and move them at will. Likewise, researchers have fashioned a unique class of molecules, called fullerenes (or "Buckyballs"), consisting of 60 carbon atoms arranged in a ball-like lattice and among the strongest materials known. Scientists also have formed such interlocked carbon atoms into extremely strong hollow tubes ("Buckytubes") and fabricated a transistor out of a single one of these molecules. Still others have built information storage devices with data bits just 50 nanometers across and a molecule that rotates and acts as a working "nanowheel."

Nanotechnology's more controversial proponents envision it as universal, self-replicating nanorobots, or "assemblers," building materials one atom or molecule at a time. While most scientists doubt that this will ever be possible, they are experimenting with other ways to build molecular structures, including traditional chemical synthesis and the use of scanning tunneling and atomic-force microscopes (which let them "push" atoms and molecules into place). Researchers can now make single molecular structures in the laboratory; however, they have yet to find a cheap and commercially feasible way of mass-producing them. (Writing in *Technology Review*, David Rotman reports that, using today's technology, building a single computer chip one atom at a time would take 1,000 years!) One answer may lie in a process called "self-assembly." In contrast to self-replicating assemblers, self-assembly relies on chemistry to position atoms and molecules, taking advantage of certain molecules' abilities to arrange themselves in complex structures (Rotman, 1999).

Nanotechnology Today

Among researchers working in the field today, nanotechnology is generally viewed as technology arising from the exploitation of the new and improved properties, phenomena, and processes at the scale between atoms and molecules and bulk materials; that is, between 0.1 and 100 nanometers. These novel properties are due to the different behavior of things at the nanoscale as compared with either isolated molecules or larger structures.

There is a growing sense in the scientific and technical community that we are about to enter a golden new era. We are about to be able to build things that work on the smallest possible length scales, atom by atom, with the ultimate level of finesse. These little nanothings, and the technology that assembles and manipulates them—nanotechnology—will revolutionize our industries, and our lives."

Richard E. Smalley
Hackerman Professor of Chemistry, Rice University, 1999

Nanotechnology implies the direct control of materials and devices at the level of atoms and molecules. Broadly, it comprises (1) the design of atomically engineered "building blocks"; (2) the assembly of these building blocks into new, "nanostructured" materials with specific characteristics; and (3) the assembly of these materials into useful devices (World Technology Evaluation Center, 1998).

There are two overall approaches to building things at the nanoscale. The first is to etch, chisel, or sculpt such features into an existing, larger structure, using techniques such as scanning tunneling or atomic-force microscopy or various forms of lithography (the process now used to make computer chips). Nano-size gears and smaller integrated circuits are just some of the objects being fabricated using this approach, which is sometimes referred to as "top–down." The second method—and the most revolutionary—is the "bottom–up" approach: building things up from the atoms and molecules themselves. One recent breakthrough resulting from bottom–up assembly is the single-electron transistor.

In the last few years, nanotechnology has yielded products with sales totaling billions of dollars, including giant magnetoresistance multilayers (for computer memory, magnetic brakes and motors); nanostructured coatings (for data storage and the photographic industry); nanoparticles (drug-delivery devices in pharmaceuticals and colorants in printing); and nanostructured materials (nanocomposites and nanophase metals). It is revolutionizing virtually every area of technology and will have a direct and dramatic impact on transportation.

Impacts of Nanotechnology

Nanotechnology's potential benefits are broad and pervasive; lighter, efficient cars through the use of nanoparticle-reinforced materials; a cleaner environment using minuscule "traps" that remove pollutants; computers with today's capabilities that are the size of a grain of sand; tiny medical probes that diagnose disease without damaging tissue; and robotic spacecraft that explore the solar system, and perhaps even the nearest stars, and yet weigh only a few pounds. Among the breakthroughs that we may see within the next several years will be the following:

Information Technology. Researchers have begun making electronic wires and components, as well as actual devices, out of single molecules. The successful development of molecular electronics would mean that a single computer chip could hold billions of miniscule transistors, making computers orders of magnitude more powerful than they are today (Rotman, 1999). Moreover, we could see computer storage devices with multi-terabit capacities—100 times better than today—and integrated sensor systems that collect data using minimal power, space, and weight.

> **"It is abundantly clear that we are now able to nanostructure materials for novel performance."**
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> **Richard W. Siegel**
> **Robert W. Hunt Professor,**
> **Rensselaer Polytechnic Institute,**
> **1998**

Transportation applications include: (1) uninhabited vehicles (both civilian and defense); (2) advanced communication capability that obviates the need for some travel; and (3) sensors that continuously monitor and report on the condition and performance of infrastructure, vehicles, and operators.

Materials and Manufacturing. Nanotechnology will fundamentally change the way we produce materials, giving us the ability to assemble nanoscale building blocks into larger structures with unique properties and functions. Today we perceive only the tip of the iceberg: lighter, stronger, and programmable materials, and reduction in costs through longer service life and lower failure rates. Over the longer term, molecular assembly could permit the development of unique "tailored" structures that have not previously been observed in nature.

Transportation applications include: (1) nanocoating of metallic surfaces to achieve super-hardening, low friction, and enhanced corrosion protection; (2) tailored materials for vehicles and infrastructure; and (3) "smart" materials that monitor and assess their own status and health.

Aeronautics and Space Exploration. Two forces compel the reduction in the size, weight, and energy consumption of spacecraft: the high cost of fuel required to lift payloads into earth orbit and beyond, and the desire to send spacecraft away from the sun (resulting in diminished solar power) for extended missions. Nanotechnology will permit the ultra-miniaturization of space systems and equipment, including the development of smart, compact sensors; miniscule probes; and microspacecraft. Moreover, advanced materials developed through nanotechnology will meet the strength, weight, and thermal stability requirements of space planes, rockets, and space stations.

Transportation applications include: (1) low-power, radiation-hard computing systems for autonomous space vehicles; (2) tiny instrumentation for microspacecraft; and (3) advanced avionics.

Environment and Energy. Nanotechnology has the potential to improve dramatically our environment and energy use. Nanosensors could be used to monitor and clean up environmental problems and to control emissions from a range of sources. Nanotechnology also could make possible new, "green" processing technologies that minimize the generation of undesirable by-products.

Transportation applications include: (1) materials that replace metallic components in cars — those now being developed could reduce carbon dioxide emissions by more than five billion kilograms a year; (2) replacement of carbon black in tires with nanoparticles of inorganic clays and polymers, leading to tires that are environmentally-friendly and wear-resistant; and (3) carbon-based nanostructures that serve as "hydrogen supersponges" in fuel cells (Jacoby, 1998).

Topics for Discussion

- What will be the major innovations in transportation resulting from applications of nanotechnology over the next 25 years?
- When will nanotechnology's impacts on transportation first be felt? On vehicles? On infrastructure?
- What will advances in carbon-based nanostructures ("Buckyballs," "Buckytubes," and "Buckywires") mean for transportation? What potential new information and communication capabilities will emerge?
- How close are we to realizing the ability to develop smart, tailored materials for transportation infrastructure and vehicles?
- What can government and the transportation industry do to prepare for, and perhaps to expedite, successful transportation applications of nanotechnology?

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Transportation Workforce for the 21st Century—A Challenge to Education

Peter A. Manning

Introduction

As the world enters the 21st Century, the relationship of education and training to the development of America's talent base continues to be a major factor in the success of the nation's ability to succeed and to excel. The United States has been fortunate in the payback received from its investment in learning at all levels. But past achievements and investments do not ensure future success. This paper provides an insight into the role of transportation education in transforming the nation's workforce. It then examines several additional areas that will impact on future developments.

Formal education programs and training efforts have not always been a determining factor in transportation innovations. Up until the early 20th century, transportation issues were part of the academic agenda, but did not have a specific framework of their own. In the 1950s and 1960s, education endeavors in transportation were concentrated at the collegiate level; mainly through engineering programs. The focus was on the practical matters of building and maintaining America's growing land, marine, and air-based systems. In the latter part of the 20th Century, transportation education became a discipline in its own right, not just an adjunct to other education programs. At the same time, there was growth in technical-oriented programs with a practitioner focus at the junior and community college level.

The historical progression highlights the first workforce issue: a need for a curriculum that educates individuals beyond the traditional, formal technical requirements of engineering and science. Developments in the field now come about because of continuing demands and commitments at several levels. The traditional focus of the engineering curricula is now supplemented by "soft skills" that stress management concepts (e.g., working in multi-disciplinary teams) and policy issues (e.g., moving beyond the needs of local society to cover global issues).

Transportation professionals in the 21st Century must have the ability to see how their work impacts the environment; not only in the cost to the air, land, and water, but also in energy use. They must have skills to understand how their decisions relate to community stakeholders (i.e., the politician who may make the decision and who provides or withholds support; the taxpayers who pay the expenses; the public who benefits from their efforts). At the same time, there is the ongoing upgrading of the curricula, based on the impacts of technology on infrastructure development, communications, and product design.