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Development of Transportation Engineering Research,Education, and Practice in a Changing

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Abstract: Transportation has been one of the essential areas within civil engineering since its early days. In commemoration of the 150th anniversary of ASCE, this paper presents a review of developments in research, education, and practice in transportation engineering. The review is based primarily on the issues of the *Journal of Transportation Engineering* over the past several decades. Main topics include transportation engineering practice, airport and highway pavements and materials, design and safety, planning and operations, pipelines, technology, and education. Historical appraisals and the current state-of-the-art for these topics are discussed. In conclusion, future directions in transportation engineering as a result of advances in technology and the attendant changing need of the transportation engineering profession in the 21st century are addressed.

Introduction

Transportation has been one of the essential components of the civil engineering profession since its early days. From time im- memorial, the building of roads, bridges, pipelines, tunnels, ca- nals, railroads, ports, and harbors has shaped the profession and defined much of its public image. As cities grew, civil engineers became involved in developing, building, and operating transit facilities, including street railways and elevated and underground systems. The role of civil engineers in providing transportation infrastructure to accommodate a growing population and economy was never more prominent than in the United States around the late 19th century and the early part of the 20th century. Transcontinental railroads, national highways, canals, petroleum and natural gas pipelines, as well as major urban transit systems,

are testimonials to the achievement of civil engineers. And, in the latter part of the last century, these achievements played a major role in developing the Interstate System, new rail transit lines, andmajor airports.

In the last 150 years, railroads, transit lines, ports, and airports have helped to increase the range of cities and reduce the isolationof rural areas. They have brought the nation closer together. Such major bridges as the Eads Bridge in St. Louis, the Brooklyn and George Washington Bridges in New York City, the Golden Gate and Bay Bridges in San Francisco, and the Mackinac Straights Bridge in Michigan have not only spanned major water crossings,but have also become a dramatic part of the national landscape

(Billington 1985; Gies 1996; Petroski and Kastenmeier 1996). The great railroad terminals—sometimes electrified with tunneled approaches, as are Penn Station and Grand Central Terminal in

New York, and the Union Stations in Chicago and Washington, D.C.—continue to serve as major gateways and urban monu-ments. The subway, elevated, and commuter rail lines built over the last century have made the centers of cities such as New York,Washington,

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sien 2001). Also, the Interstate Highway System has changed the national landscape. These are a few of the many transportation contributions to the nation by members of the civil engineering profession (Fig. 1).

To commemorate the 150th anniversary of ASCE, this paper has been prepared to document the development of the transportation engineering field within civil engineering. The paper provides a historical appraisal of how the field evolved to its current state-of-the-practice as well as a preview of future directions, and it draws heavily on volumes of the *Journal of Transportation*

The *Journal*'s roots go back to the early years of ASCE, the first issue appearing in 1874. It currently contains the technical and professional articles of the Air Transportation, Highway, Pipeline, and Urban Transportation divisions of the Society. The planning and design continue to be the core of the transportation engineering field, such areas as operations, logistics, network analysis, and financing and policy analysis are also important to civil engineers involved in the transportation field.

Another source of information, to gauge the relative emphasis placed by civil engineers in recent years on the need for new knowledge, can be attained by reviewing the papers published in the past several decades in the JTE. As the papers represent scholarly interests, which in turn should respond to the needs of the profession over a long period of time, an assessment of the state-of-the-art is presented in the next few sections (Fig. 3).

Highway and Airport Pavements and Materials

The Role in the Field

One hundred and fifty years ago, most roads between cities were unpaved except for a few plank roads. The power stone crusher (1858) and the steamroller (1859) made the use of crushed stone feasible for rural roads. Cobblestones and untreated blocks were used in cities. The first brick pavement was built in Charleston, West Virginia, in 1871, and the first sheet asphalt was placed on Pennsylvania Avenue, Washington, D.C., in 1879. In the first decade of the 20th century, portland cement concrete (PCC) was introduced in Bellefontaine, Ohio, and Wayne County, Michigan. The first theory of rigid pavement was developed at this time, andhas progressively evolved since.

Papers published in the area of pavements and materials in the *Journal of Transportation Engineering* over the past 30 years can be grouped into following categories: design, construction, materials and testing, performance analysis, and system management. Discussions that follow represent not only highway and airport pavements but also different types, such as flexible, rigid, and composite pavements.

State of the Practice

Pavement Design

The stresses and deflections of flexible and rigid pavements were analyzed using Boussinesq theory and Westergaard theory as early as 1926. Among others, Yoder (1959) pioneered the exploration of pavement design principles in the 1950s. However, a great surge of research activities and subsequent practical applications took place in pavement design as a result of the American Association of State Highway Officials (AASHO) Road Test, which was conducted in Illinois from 1958 to 1960. Using data from that test, a set of widely accepted pavement design procedures for new construction or reconstruction, overlay, and rehabilitation of pavements was developed and first published in 1972, with the latest revision in 1993 (AASHTO 1993). For flexible pavements, selecting optimal thickness of various pavement components to achieve minimum total pavement costs was an important topic of investigation among researchers (Hegal et al. 1993; Garcia-Diaz and Liebman 1978). With regard to rigid pavement design, appropriate joint design and design of concrete block pavements were extensively explored (Fordyce and Yrjanson 1969; Rada et al. 1990). Recognizing that increasing pavement construction and rehabilitation costs make it imperative to have a quick and rational method of designing the overlay thickness, several papers dealt with the topic of overlay design (Bandyopadhyay 1982; Fwa 1991).

Currently, there are more than 2.6 million miles of low-volume roads that typically carry less than 500 vehicles per day. Pavement design for low-volume roads is especially challenging because cost is always a major factor and alternative designs and materials can be used (Kestler and Nam 1999). Design procedures were also developed for airfield pavements in terms of magnitude of applied loads, tire pressures, geometric section of pavements, and number of load repetitions applied to pavements during their design lives (Murphree et al. 1971; Ahlvin et al. 1974; Seiler et al. 1991).

The Strategic Highway Research Program (SHRP), in the 1980s, launched a major research activity in the area of pavements and materials. As a part of this program, a comprehensive 20-year study of in-service highway pavements (long-term pavement performance, LTPP) was undertaken.

Pavement Construction

A number of papers covered the issue of compaction of graded aggregate bases and subbases (Marek 1977; Halim et al. 1993). Benefits of the use of hot-mix asphalt were investigated by several researchers (Colony et al. 1982). The technique of non-fines concrete with single-sized coarse aggregates held together by a binder consisting of a paste of hydraulic cement and water was also discussed (Ghafoori and Dutta 1995).

Materials and Testing

Along with pavement design procedures, investigations were made on properties of new construction materials as well as on recycled materials. Examples include engineering properties of soil-lime mixes for stabilization (Sauer and Weimer 1978), tensile fracture and fatigue of cement-stabilized soil (Crockford and Little 1987), low-temperature fracture parameters of conventional asphalt concrete and asphalt-rubber mixture (Mobasher et al. 1997), field studies on polymer-impregnated concrete (Mehta et al. 1975), and service lives of pavement joint sealants (Biel andLee 1997).

Examples of testing procedures for pavements and materials include variably confined triaxial testing, fatigue response of asphalt concrete mixtures, rut susceptibility of large stone mixtures, viscoelastic behavior of asphalt concrete, field impregnation tech- niques for highway concrete, moisture content in PCC pavements, and back calculation of moduli of pavement layers (Allen and Thompson 1974; Chen et al. 1977; Uzan 1994). The LTPP program also addressed key questions about the revised resilient modulus laboratory tests and procedures. They are geared to high-way engineers, laboratory managers, and technicians.

Performance Analysis

The pavement serviceability-performance concept was first intro- duced by Carey and Irick (1960). To study the performance char- acteristics of flexible pavements, Hertz's theory of the deflection of an elastic plate on a fluid subgrade was used (Wiseman 1973). The relationship between the cumulative peak pavement deflections and condition of that system, the stress/strain response of asphalt concrete under cyclic loading, threshold values for friction index, and crack propagation between beam specimens and lay- ered pavements were also investigated by a number of researchers (Highter and Harr 1975; Ramsamooj et al. 1998; Fulop et al. 2000; Castell et al. 2000).

The breaking load for rigid pavements was studied in early 1970s (Ghosh and Dinakaran 1970). Later, the use of finite-element analysis of pile-reinforced pavement systems was also introduced (Tabatabaie and Barenberg 1980). In the mid-1990s, the issue of probability that a continuously reinforced concrete (CRC) pavement section with a certain amount of distress manifestations would last at least a certain number of equivalent single axle load (ESAL) applications was addressed (Weissmann et al. 1994). By modeling a pavement structure as a beam resting on a viscoelastic foundation, a physical picture associating vehicle dynamics, road profile, and pavement response in a theoretical framework was constructed recently (Liu and Gazis 1999).

Lack of strain characteristics of rigid pavement overlays, the susceptibility of overlays to abrasion wear, fuel spillage, and stripping led to the research on this topic (Al-Qadi et al. 1994). The fracture behavior of interface between interlayer and asphalt overlay as well as the entire overlay pavement system was studiedin recent years (Tschegg et al. 1998).

System Management

An increasing interest could be seen in the area of pavement system management over the past two decades. A framework for pavement management systems was the topic of several papers (Findakly et al. 1974; Kilareski and Churilla 1983). Utility theory was introduced in pavement rehabilitation decisions in the mid- 1980s (Mohan and Bushnak 1985). An integrated project-level pavement management model, consisting of life-cycle cost analy- sis and cost-effectiveness method, was developed in the same period (Rada et al. 1986). In later years, a framework for evaluating the effects of pavement age and traffic loading on pavement routine maintenance effectiveness was introduced (Al-Suleiman et al. 1991). Integrating pavement and bridge programs started to appear in mid-1990s (Ravirala and Grivas 1995). Project-level optimization and multiobjective optimization for pavement maintenance programming began to be implemented in recent years (Mamlouk et al. 2000; Fwa et al. 2000).

Transportation Design and Safety

Historical Appraisal of the Field

During the 20th century, the private automobile in the United States went from being rarely sighted to a ubiquitous presence as the supporting road system was methodically expanded and im- proved, making automobile use safe and convenient. As engineerswere successful in these undertakings, the dependence of the pub-lic on other modes of transportation generally eroded. While other modes remain important, the domination of the automobile is, nonetheless, fairly complete. To be sure, the emergence of the automobile meant unprecedented freedom of movement for the population and is closely tied to the continued growth of the American economy. However, problems associated with its use are also widespread, such as urban sprawl and air pollution (Altshuler et al. 1993).

The transportation engineers have been engaged in a constant struggle to make the system safe and to overcome congestion, whether of horse-drawn vehicles in New York City long ago or onLos Angeles' freeways. Although the rates of occurrence of crashes and fatalities are lower than ever, the absolute numbers are still high (BTS 2000). For congestion, the engineer's responsehas largely been to increase system capacity. This has proven to be a short-term solution in the larger urban areas. Congestion, once restricted to the downtown areas of our older cities, now occurs daily in suburban areas as freeways are extended, arterials are widened, and local roads are designed to ever higher stan- dards. The lack of adequate and continuous streets in many sub- urban settings, coupled with the lack of effective land-use con- trols, overloads many major arterials. And public transport serviceremains inadequate to provide congestion relief in suburban cor- ridors, especially for circumferential trips. At the outset of the 21st century, many components of our transportation system are fast approaching or have already exceeded their design lives, and much of the vaunted roadway system is suffering from wear and tear due to higher than expected use. Since the era of building large systems or substantially enlarging existing ones seems to be at an end (except, perhaps, for new transit lines), the major challenges are now to rebuild the transportation system in place and touse it more efficiently and responsibly (Fig. 4).

State of the Practice

As in many fields, there appears to be a gap between the practitioner in the field and the cutting edge of research in system design and safety. Researchers dealing with issues in these areas are largely ‘‘tinkering at the margin’’ or with high-tech applications in order to develop suggestions for making the system still safer and operationally more efficient. Unfortunately, practitioners are often put in a position of taking more and more ‘‘on faith.’’ The information explosion in transportation-oriented journals has put day-to-day exploration of new findings beyond the attention span of end users. For example, the widely used *Highway Capacity Manual* (HCM) has gone from a primer on highway operations to a complex treatise that requires a solid background in traffic flow theory to even begin to understand it. Calculations of volume-to-capacity ratios and levels of service that were done with an adding machine and slide rule now require special-purpose software with routines that, for many practitioners, defy understanding or are simply viewed as a black box that may or may not work. While large agencies can and do employ transportation engineers who are specialized enough to understand these evolving approaches, there are many transportation engineers whose duties are so broad as preclude ‘‘keeping up’’ across the board.

Concurrent with evolving technology and burgeoning information, the safe use of the highway system has moved from being solely the user’s responsibility to a model of shared responsibility that includes the users, the system providers, and the vehicle manufacturers. Notwithstanding this shared model, tort liability still looms large as a driving force in transportation safety-related endeavors. Indeed, in some instances it can be argued that there are institutional constraints to both the identification of problems on the highway system and the implementation of reasonable solutions due to the exposure that a state might incur if differences in opinion are publicly aired or problem sites identified.

Despite everything that transportation engineers and those in related fields know about the relative safety of the system, there is still a gap between what is really ‘‘known’’ and what is ‘‘done’’ in the field. Safety audits that find problems before crashes take place are a step in the right direction, as there remains great variation among agencies in a given state regarding when and how horizontal curves might be signed and the appropriate advisory speed determined, from paper and pencil analysis to use of sophisticated in-vehicle equipment to a guess in the field. Providing safer and more consistent designs remains a challenge. Given that the treatment of highway curves goes back virtually to the first road, it is alarming that there is still a significant divergence in deciding on treatments within a given state, let alone among states. The litany of problems being dealt with by transportation engineers as the 21st century is embarked upon is not that different from a similar list compiled 100 years ago—progress has been made, but much remains to be done.

Transportation Planning and Operations

From Wellington’s classic study of railroad location (1887) to contemporary multimodal corridor studies, the planning of transportation facilities has been an integral part of civil engineering profession. While the scope and focus of these activities has evolved and broadened, planning continues to be a major effort. Civil engineers developed the first systematic comparison of urban land use, formulated the methods for forecasting future travel demands (trip generation, trip distribution, mode split, and traffic assignment), and analyzed spacing requirements for urban freeways (Peterson 1960).

The Role in the Field

The role of planning in transportation is vital for strategic or tactical evaluations and predictions of travel demands, land use patterns, and air quality issues for various transportation modes for both passenger and freight movements. The body of knowledge about planning, traffic operations, control, and management has witnessed drastic growth over the past several decades, and papers published in the *Journal of Transportation Engineering* have contributed to this growth. The information published in the *Journal* mirrors the need to share experiences about problems facing engineers and planners, new technologies being deployed to help remedy the situation, what worked and what did not work, and the academic contribution to improve the understanding of why and how to use basic and applied research to solve these problems.

Planning and operations appear most prominently in the field of traffic engineering for surface transportation. However, transportation engineers also confront planning and operations issues in facility management, particularly for large complexes such as airports. Transportation engineers also often become involved with urban-planning processes in developing long-term transportation plans.

State of the Practice

Transportation Planning

Before the 1960s, transportation planning was primarily an exercise in physical planning. In the past several decades, however, such plans have been perceived as inadequate for meeting social needs. Important political, economic, and social trends that have affected the evolution of transportation planning include fiscal austerity as a theme of government policy, changing roles of automobiles, environmental concerns, and changing household characteristics, among others.

Since 1945, air transportation has seen tremendous growth, with ever-increasing levels of enplaning passengers and airfreight tonnage. In recent years, air transportation planning has attracted much attention as the design and operation of this mode of transportation is associated with long lead times of large investments. The cornerstone of airport planning over the past 20 years has been the Individual Airport Master Plan for commercial as well as general airports, as approved by the Federal Aviation Administration (FAA) (Fig. 5).

A large number of research studies have been conducted in transportation planning since the 1970s. Papers published in the *Journal* focused on a vast array of planning issues, ranging from political processes of planning (Ellis 1973), examination of modal split in recreational transport planning (Theologitis and Powell 1984), longitudinal assessment of transportation planning forecasts (Miller and Demetsky 2000), airport environmental planning practices (Orlick 1978), and present and future characteristics of air-transport infrastructure planning (Coussios 1991).

Traffic Operations

The construction of the freeway system started in the mid-1950s and spanned a decade. By the late 1960s the interstate system was completed except for short sections located in urban areas. Traffic increased at a much faster rate than forecasted, especially in urban areas. This resulted in congestion, excessive delays, and pavement deterioration.

Papers published in the 1970s addressed topics like better design of traffic control devices (Payne 1973), developing and improved traffic operations programs (La Baugh 1971), freeway congestion and roadway and street capacities (Priestas and Mulinazzi 1975), and improving on traffic data collection and weigh-in-motion (WIM) (Machemehl et al. 1975). Papers related to free-ways in Chicago and Los Angeles in terms of congestion characteristics and traffic management strategies were published during this time period (McDermott 1980). The strategies of traffic surveillance ramp metering and Variable Message Sign (VMS) were discussed and tested at a few locations. At the city-street level, testing of new signal controllers and timing schemes were investigated and new traffic management strategies like signal priority strategies to special vehicles, parking controls, and signal coordination and optimization were conceived (Michalopoulos et al. 1978). Because of the complexity of road construction and maintenance and the potential risk to motorists and workers, negligence-suit and tort-liability issues were raised and studied.

In the 1980s the transportation profession witnessed major changes from the introduction of personal computers. Computing power became more affordable, and advancements in microelectronics and integrated circuits have resulted in better and smaller traffic controllers, video cameras, and loop detectors. Research related to incident detection on freeways was expanded and produced some better understanding of how traffic bottlenecks happen on freeways (Ahmed and Cook 1980). More sophisticated mathematical models were developed to better detect freeway-capacity-reducing incidents and estimate their impacts on traffic delays. More traffic surveillance strategies were demonstrated and tested on urban freeways. The microscopic simulation models that were developed in the 1970s to simulate street and freeway traffic like NETSIM and FREESIM became more attractive to research (Rathi and Santiago 1990; Cheu et al. 1998). The use of signal coordination software like PASSER and TRANSYT became a reality for some state agencies, and papers were published to educate the average traffic engineers about what the software can do for them (Jovanis and Gregor 1986; Chang et al. 1987). The ASCE's Urban Transportation Division sponsored three specialty conferences on microcomputer applications, and a large number of papers presented at those conferences were refereed and published (Skabardonis 1986; Matthias et al. 1987). Computers also enabled extensive analysis of complicated systems such as airport operations or alternative development-transportation plans.

More and more of our streets and highways are deteriorating, and work zone operation and safety emerged to be a concern to the profession. The capacity of a freeway section or an arterial passing through a work zone was researched, and the results were well documented (Nemeth and Rouphail 1983). Knowledge-based expert systems were introduced as research and education tools to build on knowledge accumulated over the last few decades. The idea of tapping the expertise of an expert and mimicking his decision process using computer software caught on fairly fast. Some applications to this concept included traffic signal timing, budget allocation, traffic-crashes management and inventory, and pavement cracks recognition (Zozaya-Gorostiza and Hendrickson 1987; Lin 1991). The introduction of an adaptive signal control took place in the late 1980s. The idea here is to take advantage of improvements in signal-controller enhancements and better detection systems to make the controller more responsive to changes in traffic patterns at intersections. Initially, the work was fairly limited to short-term future flow patterns (Lin and Vijayakumar 1988; Young 1989), but it is now expanding.

The enhancement of software and hardware continued successfully through the 1990s. The price of personal computers continued to decline until about 1993. The industry held the price fairly constant and offered more power in terms of speed, memory, and storage capabilities. Graphical representation and three-dimensional visualization became possible and affordable in the late 90s. Traffic-simulation software became versatile and available to most local and state agencies to use for conducting technical studies as well as demonstrations in public hearing and decision making. Geographic information systems (GIS) is an offspring of this computing revolution (Abkowitz et al. 1990; Quiroga and Bullock 1996). The ability to integrate different databases into one system and then overlay information in different colors and layers has helped us to better understand how the aspects of the system interact, and it assisted us in making better decisions based on a sound approach.

Neural networks appeared on the research scene as a new and viable tool of simulating the human brain. Applications of neural networks included incident detection techniques, crash-type identification and recognition, data warehousing, and data mining (Nam and Drew 1998; Wolshon and Taylor 1999).

The evolution of the ITS discipline has given the transportation profession great opportunities and challenges. There were opportunities that allowed us to take advantages of advanced technological innovations that were created in the 1980s under defense contracts to be used in traffic operations and control. Examples of these innovations include image processing and machine vision, wireless communications, global positioning systems (GPS), high-speed networks, parallel processing, detection systems using laser, and others (Bullock and Hendrickson 1992). The challenges created by ITS are mostly political and social. The transition occurred rapidly without educating and training a cadre of professionals about what technology can do for them and about the complexity of incorporating the diverse population of motorists on transportation systems. Furthermore, transportation corridors cross several jurisdictions and counties; coordinating the communication, command, and control among those entities is a great barrier. The fact that we can install transponders and telematics on our vehicles permits us to receive real-time information around-the-clock about the status of the network, signal distress signals in case of emergencies, use toll roads without having to stop, and avoid collisions with other vehicles and fixed objects. The major hurdle of doing all that is the privacy issue and the acceptability of such systems.

Because of ITS deployment programs and the substantial funding invested in this discipline, large number of research activities and technical papers were reviewed and published. Some topics include dynamic traffic assignments, data mining, electronic toll collection, collision detection and avoidance using GPS, vehicle detection using laser and image processing technologies, and real-time information given to motorists. The use of wireless communication allowed researchers to collect more accurate data about behavior of traffic under different conditions. This data has been used to revisit the theoretical models that were developed two decades ago and fine-tune them.

Pipelines

The first pipeline was developed in 1865 to transport oil from northwestern Pennsylvania to a railroad station six miles away. The first long distance pipeline was built in 1878; the six-inch, 100-mile pipeline connected Corryville and Williamsport, in Pennsylvania. Today more than 225,000 miles of pipeline account for one-sixth of the total intercity ton-miles (BTS 2000).

Role in the Field

Pipelines represent a unique mode of freight transportation. Although the role of pipelines in the entire transportation sector is not large, it serves very specialized needs, and the *Journal of Transportation Engineering* has the distinction of serving as a forum for publishing new knowledge in this area. A review of the papers on pipelines published in the journal over the past three decades indicates the following major areas of interest: pipeline infrastructure engineering (consisting of design, testing, and construction); safety; economics, and implementation policy issues—all discussed below.

State of the Practice

Pipeline Infrastructure Engineering

This area involves such topics as design and testing, stress analysis in pipe junctions, corrosion, settlement, and soil/pipe interactions. There were several papers on pipeline design, including partially embedded pipes (Olander and Robertson 1970; Olander and Davidson 1980), undersea aqueduct design (Armstrong 1972), testing of large diameter pipes under combined loading (Bouwkamp and Stephen 1973), and surcharge loads on buried pipes (Shmulevich and Galili 1986; Potter 1985). To study the problem of stress at pipe junctions, finite-element methods were used in early 1970s (Godden 1973). In the same period, an extensive review of pipeline corrosion and corrosion control was carried out (Kinsey 1973). In the mid 1990s, the issue of corrosion was revisited by using probabilistic modeling (Ahammed and Melchers 1994).

The Soil Pipe Interaction Design and Analysis (SPIDA) program, developed by the American Concrete Pipe Association (ACPA), was a culmination of over 20 years of research and testing for improved methods of estimating load and pressure distribution on buried concrete pipes. The differences between the traditional indirect design method and the direct design using SPIDA program by analyzing an actual installation was researched in early 1990s (Kurdziel and McGrath 1991).

Some major pipeline construction projects implemented over the last three decades included the Trans-Alaska pipeline project and the Similkameen pipeline suspension bridge at Princeton, British Columbia (Patton 1973; Chen and McMullan 1974). In addition, the construction of the Dallas water distribution system, the Schuylkill River major crossing project at Philadelphia, and the Water System Improvement Program at Eugene, Oregon, also took place in the same period (Hudson 1974; Missimer 1978; Brown 1980) (Fig. 6).

Safety, Economics, and Implementation Policy Issues

The Federal Natural Gas Safety Act of 1968, a major milestone in pipeline safety, required enforcement of minimum safety standards, record-keeping, compliance with maintenance standards, reporting of safety activities, and the development of reasonable and proper safety standards. The practice of Illinois Office of Pipeline Safety was discussed by Shutt (1972). A procedure for seismic risk probability analysis of buried pipelines was developed by Mashaly and Datta (1989). Accidental detonation of explosives near pressured gas pipelines may have severe consequences on pipelines. By taking into consideration the characteristics of explosion source, soil, and the pipelines, a prediction model for the safe distance of a pipeline from an explosion source with known explosive quantity was developed by Rigas and Sebos (1998).

In the early 1970s, economic evaluation of slurry pipelines was conducted by Wasp et al. (1971) in terms of reliability, immunity to escalation, minimal maintenance and operation personnel, and esthetics. Osborne and James (1973) applied the concept of marginal economics to pipeline design, obviating the need for a considerable amount of calculation normally required. Based on an annualized cost approach, comparison of pipeline with a rail and truck economy was made by Zandi et al. (1979), who indicated that pipeline was reasonably attractive in terms of per ton-mile of transport.

Several papers dealt with implementation policy issues. For instance, right-of-way aspects were addressed by Stastny (1972). Issues of acquisition of subsurface information for pipeline construction, cost, and, applicability as well as the contractor's use of and reliance upon such information were discussed by Carter (1978). In the same period, studies were conducted on criteria and procedures required in the preparation of design, construction methods, pipeline river crossings (O'Donnell 1978). Trends in environmental regulations and their implications were also analyzed (Barningham and Ott 1980).

Technology in Transportation Engineering

Role in the Field

The major technology concepts of current transportation engineering were generally in place by the midpoint of the 20th century. Among others, notable technologies include the internal combustion engine with petroleum-based fuel for land and water transport, construction of all-weather roads, standardized signals and signs (longitudinal center stripes on roadways appeared in Wayne County, Michigan, as early as 1911), and intercity train speeds attained in the early 20th century.

Despite the stability of such fundamental concepts, there have been major improvements in the underlying technologies for airplanes, trains, motor vehicles, concrete mixes, system operations, and others. At the same time, information technology applicationshave been widely developed and applied within transportation engineering. New concepts have had profound effects, such as containerization for freight transport. Regulatory requirements have spawned new technologies, such as the requirement forhandicapped access to public transit.

State of the Practice

The *Journal of Transportation Engineering* provides an interesting perspective on the introduction of new technologies into transportation engineering. The various special issues devoted toa single subject or application are good starting points. Since the creation of the *Journal* in its current form in 1983, there havebeen eight special issues with related sets of topical papers: expert systems in transportation engineering (1987); high-speed rail (1989); robotics and automatic imaging (1990); Intelligent Vehicle and Highway Systems (IVHS) (1990); real-time traffic control systems (1990); hazardous materials transportation (1993); advanced traffic-management systems (1993); and high-speed ground transportation (1997). Each special issue had a componentof new technology and motivated continuing work.

Expert Systems in Transportation Engineering

The systems reflect a widespread interest in artificial intelligence, incorporating greater reasoning capabilities in computer software.Subsequent developments have implemented fuzzy logic and neu-ral networks technologies for transportation engineering. The motivation for this work was improved decision making by such automated systems as traffic controllers. These techniques have now become common state-of-the-practice for software engineering.

High-Speed Rail and High-Speed Ground Transportation

These special issues represent the continuing effort to redesign the U.S. intercity passenger system to become more like those in Europe or Japan. These countries have a heavy emphasis and investment in high-speed rail transportation. This redesign has faced substantial market and organizational obstacles, reflected in the paper by Harrison (1995).

Robotics and Automatic Imaging

These topics continue to be an active area of research, and com-mercial products are appearing in many areas. Equipment trainsfor asphalt roadway repaving are good examples of semiautomated procedures. Video traffic detectors are available commercially.

Intelligent Vehicle and Highway Systems

These special issues predate the expansion of this topic to the general area of ITS. Indeed, ITS technologies were featured in the*Journal* as early as 1988 (Sinha et al. 1988). Along with the special issues of real-time traffic control and advanced traffic management systems (ATMS), ITS development has represented a major infusion of new technologies into transportation engineering, for applications such as electronic toll collection (Al-Deeket al. 1997) and traffic control (Jovanis and Gregor 1986). Despite these advances, ITS remains a source of frustration because of slow implementation. For example, Chase and Hensen (1990) noted a 10-year lag in the use of new technology for traffic control applications. With the stagnation in signal control hardware, the lag has certainly increased substantially since they wrote in 1990.

Hazardous Materials Transportation

This special issue reflects new regulatory concerns and a new risk-management approach to this topic. Such changes often require new technologies. Requirements for handicapped access changed the vehicle designs and operating procedures for transit enterprises (Smith 1983). Environmental concerns profoundly influence designs (Johnston and Rodier 1999) and materials choices (Baybay and Demirel 1983). Supply chain effects also become concerns, as with the indirect energy required for transportation construction (Levinson et al. 1984).

The introduction of new technologies into transportation engineering is certainly not limited to these special issue topics. Some other major areas represented in the *Journal* include information technology for planning, design, and operations, and the invention of new control devices. The transportation engineering community has embraced new hardware and software for a variety of applications, including roadway systems management (Kilareski and Churilla 1983), traffic control design (Skabardonis 1986), and noise modeling (Cohn et al. 1983). New sensors provide data either more cheaply or in ways not previously available. Satellites provide a new vantage point for transportation engineering (Graham 1980) and much-improved location information. Field sensors are used routinely in roadway and facilities management decision making (Rollings and Pittman 1992; Uzarski and McNeil 1994).

Transportation Engineering Education

Early Professional Activities

Excluding Roman times, the 19th century railroads, and canals, one could argue that transportation education (at least in the United States) has its roots at the turn of the century, when Ford introduced the Model T and the federal government passed the Federal Aid Road Act of 1916 establishing a federal aid highway program. Those developments for the first time created an urgent need to apply scientific principles to the building of roads suitable for automobile travel. With the exception of traditional civil engineering surveying and earthwork practices, there was little reference or education material available on the engineering principles involved in building highways (Hickerson 1926). For the next 40 years, the legislative process dominated and transportation-related education primarily occurred on an *ad hoc* basis via existing organizations such as ASCE (1852) or emerging technical organizations such as AASHO (1914), the Highway Research Board (HRB 1921), and the Institute of Traffic Engineers (ITE 1930).

The first major efforts to develop reference material for educating professionals on the technology of building roads began occurring at the time of the Federal Aid Highway Act of 1938. That act directed the Bureau of Public Roads to study the feasibility of national toll roads and probably served as a motivating force to distill existing knowledge into recommended practice. This process of educating professionals on the construction of roads was initiated by AASHO in 1937 by organizing a committee to study the planning and design polices used for highways.

The AASHO effort was completed for rural highways in 1954 and supplemented in 1957 for urban highways (AASHO 1957). Parallel to the effort of developing uniform design procedures, other committees developed procedures for uniform signs, striping, and control devices (PRA 1948) and for estimating the capacity of highways (USDOC 1950). These three efforts provided much of the educational material available to professionals involved in designing the Interstate System authorized in the Federal Aid Highway Act of 1956. Educational material related to pavement design and materials emerged slightly later, from the AASHO road test that occurred during 1955–1961. Several papers previously published in the JTE have provided improvements on these initial methods and have been incorporated into the recent editions of these manuals used today (AASHTO 1994; TRB 2001; USDOT 2000).

Engaging Universities in Transportation Education

During the first part of the century, state highway departments begin to team up with local universities. For example, the Texas Highway Department partnered with Texas A&M University in 1919, and the Indiana State Highway Commission partnered with Purdue University and formed the Joint Highway Research Project (JHRP) in 1937. Although these ventures were primarily intended to address fundamental road-building issues, locating them at universities provided a mechanism for quickly injecting research findings into curricula. In addition to these joint research ventures, Harvard University developed a nine-month nondegree Certificate of Highway Traffic in 1925. That program moved to Yale University in 1938 and remained there until 1968, when it moved to Pennsylvania State University and then dissolved in 1982 (Rankin 1997). In contrast to modern funding practices for graduate education, from 1925 to 1972 the Bureau received most of its funding from foundations and other private-sector sources. In the 1970s, the education in transportation was greatly influenced by the funding made available through the university research and education programs of the USDOT and the Urban Mass Transportation Administration (UMTA). Similar programs were later initiated by the FAA and other modal agencies. In the 1980s, university transportation centers were established by the USDOT. These federal programs provided an impetus for multimodal transportation engineering education, mainly at graduate level. Currently, with the exception of a few short courses targeting very narrow topics, the dominant delivery mechanism today for transportation education is one or two undergraduate courses in a civil engineering curriculum or several courses in a civil engineering graduate degree curriculum specializing in transportation.

Emerging Textbooks and Curricula

In parallel to the ongoing research to develop these professional codes and standards, principles and practices from these efforts begin to be distilled into reference and textbook material adaptable to formal courses in the field of highway engineering. This material quickly broadened to cover other modes, system analysis, and planning (Woods 1960; Hickerson 1964; Wohl and Martin 1967). By the early 1970s, textbooks and university curricula were following two distinct paths: some undergraduate curriculums adopted more broad-based transportation references that provided introductory material to the variety of transportation modes (Wright and Ashford 1997); other undergraduate curricula adopted tightly focused references targeted specifically at highway design and construction (Mannering and Kilareski 1997).

This philosophical debate of breadth-versus-depth transportation education remained unresolved and continues today with universities struggling to address additional issues related to policy, energy, environment, and technology.

Future Directions

Planning, Operations, and Technology

During the past several decades, the transportation planning area has matured and many of the procedures are now standardized. While early efforts on developing a transportation planning framework in the late 1950s and 1960s were made by civil engineers, the transportation planning area gained much from the disciplines of economics, urban geography, and planning and regional science. In fact, transportation planning is another instancewhere the sphere of the civil engineering profession has expanded to let other disciplines enter into the transportation engineering curriculum. Travel demand estimation, data mapping using GIS, and land-use transportation modeling are some examples that bear the results of collaborations of civil engineers with economists, geographers, and planners, respectively. This trend can be expected to continue with increased use of technology and real-time planning of operational actions.

Another development in transportation education and research that has gained popularity in recent years is the area of transportation logistics. While traditional transportation engineering is concerned with the construction and maintenance of roads, bridges, and other facilities, transportation logistics involves decisions that are made by transportation carriers, as well as shippers and receivers. Long the subject of interest to management and business professionals, transportation logistics has found its way into civil engineering transportation programs over the years in the United States, indicating yet another area where the collaboration with another discipline has expanded the boundary of the civil engineering. Potential exists for much growth in thisarea.

Traffic engineering as a discipline will continue to take advantage of the information technology revolution, and alternate delivery systems of travel information and services will be pursued. Traffic operation centers (TOC) of the future will all be centralized into one physical location, with the ability to have various agencies—like freeway management, emergency response, toll collection services, and signal systems—operate in a coordinated fashion yet run independently.

Indeed, transportation engineering technology has some exciting changes underway. The development of ubiquitous computing and high-band communications networks will enable vehicles and infrastructure elements to sense their environment and to communicate to operating agencies. Transportation engineers must determine how this flood of information can be best used. Environmental concerns will also drive new technologies. Hybrid and fuel-cell-powered vehicles are appearing. Compressed natural gas is well established as a fuel for fleet vehicles. Organizational innovation may be as critical to the introduction of these changes astechnology development itself.

Pavements and Pipelines

As the LTPP data are analyzed, many of the pavement design procedures will be modified and emphasis will continue to be placed on maintenance and rehabilitation decisions. Emerging technologies will allow early detection of deterioration and nondestructive evaluation of pavements. With new high-quality materials and improved testing procedures, much progress can be expected in the provision of pavements and structures with longer lives and better service. Improved methods of data collection and monitoring will enable more reliable determination of various life-cycle costs and repair actions and associated trade-offs for maintenance and rehabilitation of both highway and airport pavements.

Similar trends can also be expected in the area of pipelines, including the use of technology in monitoring conditions. In addition, engineering and economic aspects of pipeline infrastructure maintenance and rehabilitation will remain critical, along with environmental, land use, and safety impacts.

Safety and Security

According to the World Health Organization (WHO), in 1998 road crashes were the largest cause of illness or early death for males between the ages of 15 and 44 worldwide, and the second-largest cause of illness or early death for males in all age groups in developing countries (BTS 2000). Although in the United States the fatality rate per 100 million vehicle miles of travel is lower than that of many Western European countries, more than 44,000 lives are lost each year with an estimated annual cost of more that $137 billion. Traffic safety remains a serious public health concern in both developed and developing countries, and the sustainability of automotive transportation cannot be achieveduntil the safety issue is resolved.

The trajic events of September 11, 2001, dramatically underscored the critical need for security of transportation systems. The spectre of terrorism worldwide has introduced a new dimension intransportation planning, design, and operation. The threat exists not only for air transportation, but also for the entire physical infrastructure and control for the transportation of people and goods, including pipelines, rails, waterways, mass transit, highways, bridges, and combinations of various modes and the interfaces among them. To face this challenge, transportation engineers must consider the risk and vulnerability associated with transportation facilities and services so that threats can be detected in a timely manner and measures can be taken to preserve security. Information and communication technologies will play a key part in the development of techniques and approaches to ensure the safety and security of our transportation systems.

Transportation Engineering Education and Practice

The skills required by a practicing transportation engineer no longer appear to be coincident with a general civil engineer.

Basic education must be more flexible to accommodate more specialization early in academic training. Universities and other institutions must become more actively involved in providing continuing education programs for practitioners. While some professionals will keep up with changes because of their constant use, others will need assistance, through continuing education, to stay current. The involvement of line agencies in research and development is important regardless of whether that work is done in-house or by consultants and universities. As it stands, much is done in the name of safety and better design, but both pre- and postimplementation evaluations, especially the latter, are still relatively scarce. The link between transportation systems, land-use policy, and increasing or decreasing travel demand has long been reasonably well understood. As the transportation system becomes more congested in certain areas, it is clear that even better use of new technology will not solve congestion. Nor is it always feasible to build out of congestion. What we need are long-range efforts on land-use planning and ‘‘smart growth’’ policies, along with the use of pricing and other economic investments so that other modes, such as public transportation, can be viable alternatives. Policies including freight transportation also require a renewed look so that all modes—trucking, rail, water, air, and pipeline—operate on a level playing field.

In the last three decades transportation engineering education has broadened to include a vast spectrum of subdisciplines. Nevertheless, the pace of research has quickened and transportation-related publications are being published at a rapid rate. In 1997, the *Journal of Transportation Engineering* launched a Book Review section with publications generally covering three broad areas—transit studies, introductory transportation engineering, and professional handbooks and references. Notably lacking from this list are comprehensive textbooks on the design and management of ITS systems. With recent legislation aimed at mainstreaming information technology into transportation systems, the next two decades are likely to see a mainstreaming of ITS-related education material in college curriculum. From that, we will probably see the field of transportation education broaden even further.

Conclusions

The early engineers, by their training, experience, and inclination, were often generalists. Many engineers worked pragmatically with a strong sense of physical and political reality. As the field became more diverse and complex, this was no longer possible. Growing federal, state, and local requirements called for a broad range of skills and capabilities, and new analysis tools. These new tools have in many ways transformed approaches to transportation engineering. But they have created many technical specialists who are often unfamiliar with or insensitive to many other aspects of transportation engineering. This growing dichotomy between the generalist and specialist has been aided by contemporary transportation education. Although universities have often broadened their curriculum programs, they are increasingly theoretical, sometimes at the expense of practicality; part of this dilemma stems from a growing emphasis on training for research rather than practice. It also stems from a growing number of faculty with little experience with and interest in practical matters. A related concern is how best to attract new talent. In today’s society transportation engineering, despite its promise and importance, remains far less on the cutting edge than do fields like biomedical engineering and computer science.

Advances in technology and computer capabilities in just the last decade have brought an increasing amount of information to the engineer’s fingertips for many applications. Many states have extensive files of road inventory, traffic and cost data, and access to GIS, to say nothing of ever more powerful programs that can be used for system design, analysis, and management. The systems exist but are not easily made compatible. Moreover, the extensive files often have data rife with errors. While the data were required, their subsequent use was given little importance. They were collected because they were required, not because they were actively used by anyone other than in an annual year-end report. This serves to illustrate that practicing engineers have increasing information with which to work but that few are using the information in proactive decision-making processes.

The role and need for transportation engineering will grow in the 21st century. A growing and more affluent population will increase demands for travel and improved transportation facilities and services. There will be a need for environmentally sensitive and creative designs, and ingenious management and operating strategies. There will be a need to achieve community consensus in making these a reality. Transportation engineers should be well positioned to meet these challenges. Transportation engineering in particular must provide an integrated approach that includes planning, statistics, economics, finance, public policy, operations, and management. It must provide a sense of physical, environmental, and political reality.

The transportation engineering profession in the 21st century must be able to adapt to changes in community needs and values. It must be able to plan, manage, and operate as well as build. Sound judgments and better integration of theory and practice are now essential. Flexibility and a strong sense of physical, political, financial, and environmental reality will help us in planning, designing, building, operating, and managing transport facilities in the 21st century.

Abbreviations

AASHO: American Association of State Highway Officials
AASHTO: American Association of State Highway and Transportation Officials
ACPA: American Concrete Pipe Association
ASCE: American Society of Civil Engineers
ATMS: Advanced Traffic Management Systems
BTS: Bureau of Transportation Statistics
CRC: Continuously Reinforced Concrete
ESAL: Equivalent Single-Axle Load
FAA: Federal Aviation Administration
GIS: Geographical Information System
GPS: Global Positioning System
HCM: Highway Capacity Manual
HRB: Highway Research Board
IVHS: Intelligent Vehicle and Highway Systems
ITE: Institute of Transportation Engineers
ITS: Intelligent Transportation Systems
JHRP: Joint Highway Research Project
LTPP: Long-Term Pavement Performance
MUTCD: Manual on Uniform Traffic Control Devices
NRC: National Research Council
PCC: Portland Cement Concrete
PRA: Public Roads Administration
SHRP: Strategic Highway Research Program
SPIDA: Soil Pipe Interaction Design and Analysis
TOC: Traffic Operation Center
TRB: Transportation Research Board
USDOC: United States Department of Commerce
USDOT: United States Department of Transportation
UMTA: Urban Mass Transportation Administration
VMS: Variable Message Sign

WHO: World Health OrganizationWIM: Weigh-in-Motion

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