# Advanced GIS Applications for Civil Infrastructure Systems

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**ABSTRACT:** This draft paper addresses advanced applications of geographic information systems (GIS) for decision making related to civil infrastructure systems (CIS). A functional definition for GIS is proposed that can be used to categorize databases appropriate for GIS applications. The paper provides a brief description of GIS, and includes coverage of issues such as modeling and decision support systems, interoperability, geospatial data, and advanced GIS. It is the intention of this draft paper to summarize key features and issues related to GIS to stimulate discussion and feedback for planning and participation in a National Forum on Advanced GIS Applications for Civil Infrastructure Systems.

## 1.0 Introduction

Geographical information systems (GIS) for civil infrastructure have expanded rapidly in the last several years fueled mainly by advances in computing and data collection technology. Applications of GIS have been enhanced by improvements in mathematical modeling of risk and reliability as well as systems optimization. Advances in computing and systems monitoring and data acquisition have resulted in the proliferation of GIS-based data sets pertaining to the physical, social, and economic characteristics of urban communities. The commercialization of GIS technology into user-friendly software packages has promoted the development of effective decision-making tools that can draw upon the wealth of available and expanding GIS-based data sets.

Infrastructure management in the 21st century will be shaped and guided by effective graphical representation of complex systems, accurate network simulation, risk assessment, and graphical fusion of physical and social databases. There are real barriers, however, to GIS use, such as cost and training with respect to database creation, identification and selection of relevant existing databases, difficulties in GIS interoperability because of functional and database preferences, and the absence of common GIS for many public and private sector organizations. To achieve the full potential of GIS, it is necessary to promote creative thinking about data fusion, selection and use of relevant social and physical databases, evaluation of spatial variability, and reduction of the institutional barriers to common GIS use. As Malczewski (1999) points out, GIS promotes the integration of various technologies, such as remote sensing, global positioning systems, computer-aided design, and automated mapping and facilities management. Hence, questions arise not only with respect to optimal GIS use, but with respect to the technological developments that are most likely to expand GIS use and its effectiveness.

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Recognizing the importance of GIS for civil infrastructure, this white paper is being developed to stimulate innovative thinking about GIS applications and to identify the most promising areas of emerging and future GIS use. The paper begins by defining civil infrastructure systems, briefly introducing the basics of GIS and discussing modeling, simulation and decision-making systems that can be integrated with GIS. Interoperability issues are also addressed, followed by sources of geospatial data, advanced GIS applications in civil infrastructure and the uses of remote sensing technologies for time-dependent data. This exploration of GIS and its applications to civil infrastructure leads to recommendations regarding the goals and directions for expanding the use of GIS for civil infrastructure systems (CIS).

## 2.0 Defining Civil Infrastructure Systems

Civil infrastructure systems (CIS) involve both the physical environment and the social and economic characteristics of communities that are located within the physical environment. As illustrated in Figure 1, the different aspects of CIS can be divided into the two broad categories of societal and physical environment.

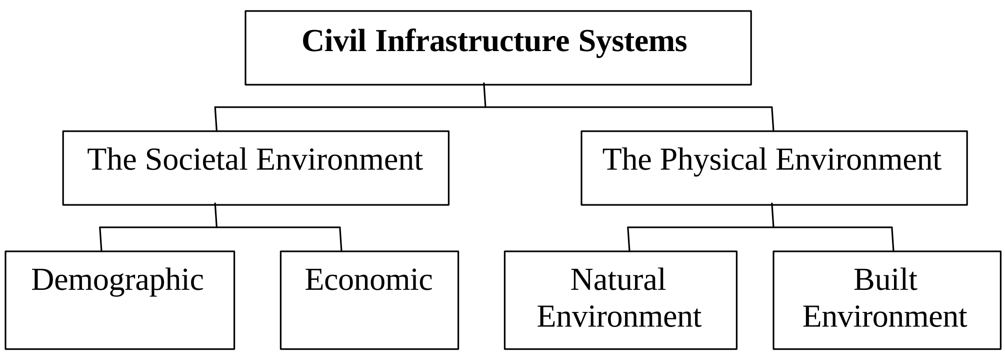


*Figure 1. Civil Infrastructure Systems*

Data about the societal environment may be divided into demographic and economic information. Demographic information includes 1) political boundaries (state, county, metropolitan areas, school/voting districts) 2) population (age, gender, marital status, race, employment, education, health) 3) housing (household size/type, utility usage, transportation use of household), and 4) human hazards/security/vulnerability (crime, terrorism). Economic information includes 1) personal and governmental income 2) personal and governmental spending 3) land and housing rent/value 4) trade (manufacturing, retail, wholesale), and 5) types of industries (service, construction and manufacturing).

The physical environment consists of the natural and built environments. The natural environment includes 1) land use and land cover 2) topography 3) geology and seismology 4) water (natural waterways, lakes, coasts, wetlands, groundwater) 5) quality of environment (air, water, soil) 6) sources of pollutants 7) wildlife/plant habitat, and 8) natural hazards and disasters (tornadoes, hurricanes, extreme weather). Elements of the built environment[3] consist of 1) public/private buildings 2) electric power (power plants, transmission lines) 3) steam, gas and liquid fuels (fuel and energy conveyance pipelines) 4) telecommunication (radio and mobile transmission towers, telephone lines, internet and television cables), 5) transportation (highways, bridges, streets, railroads, mass transit, ports and waterways, air transportation facilities) 6) water supply (dams, pipelines, aqueducts, reservoirs) 7) wastewater conveyance and treatment (collection systems, sewage mains, sewage treatment plants), and 8) solid waste disposal (landfills, ocean disposal, recycling facilities).

The shear size and diversity of CIS databases represents a significant challenge for GIS. The information pertaining to demographic trends, economic characteristics, and the natural and built environments is found in many different formats and is linked to diverse geographical units. For example, demographic and economic databases collected by the US Census Bureau are based on census tracts, which are land units encompassing 2500-8000 inhabitants with relatively homogenous population characteristics, economic status, and living conditions. The size of the land units varies depending on the population density, so that the geographic units characterized by demographic and economic data may not be consistent with the level of detail associated with geographic databases for the natural and built environment.

The quality and reliability of societal information is an important issue. Although data are available about the age and cost of residential and commercial properties from census tract surveys, this information is based on the estimates of owners and residents. More reliable information is often on file with local municipalities in the form of property assessments, but such information is rarely available in GIS format with the level of detail required to make refined evaluations.

There is a wide range of issues associated with the size and diversity of societal data sets. Data on civil infrastructure spending are available through the US Census of Governments, but this information is summarized at the county level and thus is often too coarse for refined analyses. Proprietary data sets and services are available for demographic and economic characteristics, but how reliable is this information and how well can it be coordinated through GIS with other data sets pertaining both to the societal and physical environments?

The enormous size of the societal and physical databases affects their collection, categorization, and applications. What are the most important problems that can be solved with these data sets through GIS visualization and decision support systems? What are the criteria for reliability and how much refinement in geographic units is needed to address the most important problems? Moreover, what are the barriers to database development? The acquisition of economic and demographic data involve issues of privacy, economic competition, personal security, and political preferences with respect to the role of government.

[3] O'Rourke, 1993, p.5

Strategic thinking is required with respect to the societal environment. The format, reliability, and refinement of geographic units associated with demographic and economic data needs to be considered and directions mapped with respect to the best courses of action for the future. Moreover, barriers to the development of societal data sets, arising from political, economic, and privacy issues, need to be assessed so that the possibilities and limitations of data collection can be clarified not only on a technical basis, but a societal basis as well.

## 3.0 Geographic Information Systems

GIS can be thought of as a system for integrating data from various disciplines and formats to develop information about a specific geographic area or site. GIS differs from other management information systems in that its databases are primarily associated with a spatial coordinate system. GIS has the capability of receiving inputs of tabular data, map data and remotely sensed data, and producing outputs of reports, maps and statistics. GIS is related to and linked with database management systems (DBMS), statistical programs, computer aided design (CAD) and image processing, as illustrated in Figure 2.

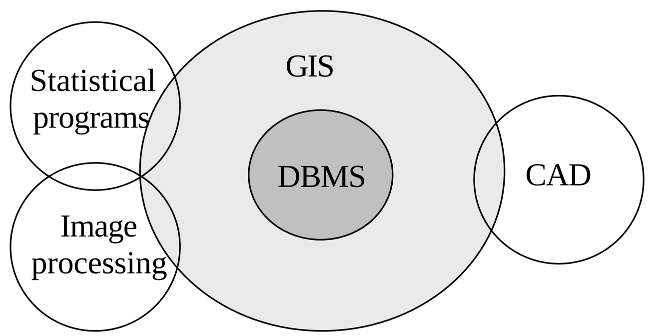


*Figure 2. Relationships between GIS and related computer systems*

GIS can be used with both vector (points, lines, polygons) and raster formatted data. Database operations can be performed on non-spatial data, individual spatial layers, and multiple spatial data layers. Functionalities/operations of a GIS include data selection and query, spatial aggregation and generalization, buffer zones, geometric transformation, geo-referencing, overlay operations, topographic operations, linear operations, and spatial interpolation.

Different types and formats of geospatial data are available for use in a GIS including line data for roads and streams, elevation data, aerial photography and land characteristics data. A summary of common types of digital geospatial data is found in Table 1.

*Table 1. Summary of Types of Digital Geospatial Data*

| Database | Scale | Description |
|---|---|---|
| Digital line graph (DLG) | 1:24,000<br>1:100,000<br>1:2,000,000 | Vector map consisting of various georeferenced thematic line layers such as roads and streams |
| Digital elevation model (DEM) | 1:24,000<br>1:250,000 | Raster representation of elevation |
| Digital raster graphics (DRG) | 1:24,000 | Image of USGS standard series topographic map, georeferenced to Universal Transverse Mercator (UTM ) projection |
| Digital orthophoto quads (DOQ) | 1:24,000 | Digitally altered image of aerial photographs where displacements caused by camera and the terrain have been removed |
| Land use/land cover (LULC) | 1:100,000<br>1:250,000 | Derived from aerial photographs; classified into 9 categories: built-up land, agricultural land, rangeland, forest land, water, wetlands, barren land, tundra and perennial snow or ice; coarse and outdated in areas of rapidly changing land use |
| Multi-Resolution Land Characteristics (MRLC) | | Contemporary nation-wide land cover data; classification done from Landsat Thematic Mapper and Advanced Very High Resolution Radiometer (AVHRR) imagery and other ancillary data sets |
| Geographic names information system (GNIS) | N/A | Official repository for U.S. physical and culture name-places; useful for digital line graphs (DLG) |
| TIGER files | 1:100,000 | The Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) line files; a digital database of geographic features, such as roads, railroads, rivers, lakes, political boundaries, census statistical boundaries, etc. covering the entire U.S. |

## 4.0 Analytical Modeling, Simulation, and Decision-Support Systems

One of the reasons that GIS has become so valuable is due to its ability to integrate with more advanced data processing systems. The integration of analytical modeling, simulation and decision-support systems can significantly increase the functionality of GIS. The following sections provide examples of how these linked systems enhance GIS applications for CIS.

*Analytical Modeling and Simulation*

Analytical modeling and simulation are often used for revealing and predicting the patterns and behavior of the natural environment such as wildlife migration, groundwater movement, contaminant migration, weather, and earthquakes. It has also been applied to traffic pattern prediction, rural/urban migration and transportation routing. Analytical modeling uses mathematical algorithms to describe physical occurrences.

Simulation is used when the behavior of system cannot be easily formulated into mathematical equations. Integrating these models with GIS allows the user to visualize the model and manipulate the data from the model to better understand and make decisions concerning its effects on the system in question.

An example of simulation and GIS is the development of an Urban Simulator by researchers at UCLA's Department of Architecture. The Urban Simulator is a "visualization system which provides high quality photo-realistic simulations of selected communities and neighborhoods." [4] The simulation allows the user to walk through the streets and view the buildings and structures in a 3-D format. Changes can be made to the photographs, which then can be visualized and evaluated before the changes are implemented. Search and retrieval tools that can be used to identify existing problems and evaluate alternative solutions.

One of the applications of the Urban Simulator involved simulating a proposed ordinance that required property owners to plant trees in front of their properties. The simulator was used to demonstrate the effect of the ordinance on the neighborhood based on sales data. GIS was used to query the sales data and provide the information for the simulation. This technology could be used to visualize and evaluate urban planning strategies, street design, utility network design (above and underground) and maintenance of infrastructure. For example, pictures of streets could be kept and updated in a GIS, allowing for difficulties in repair (due to traffic, new construction) to be anticipated beforehand.

*Spatial Decision-Support Systems*

Spatial decision-support systems (SDSS) go even further by integrating decision-making into the system. In Malczewski (1999), decision problems are described to range from unstructured, where the system presents options that the user must decide on, to structured problems, where the expert’s decision-making skills are essentially programmed into the system. Few, if any, decisions are purely structured or unstructured. For example, locating a facility may seem to be fairly structured if the criteria are well specified (i.e. located near major streets, away from other similar facilities, zoning). However, issues, such as community resistance or environmental effects, may not be as easily programmable. Spatial support systems are generally categorized into four types: [5]

1. *Spatial Data Processing Systems (SDPS)* have data, procedures, evaluation criteria and constraints, and strategies that are well defined. The decisions are essentially made after the system is run and there is no need for decision-makers to go through a problem-solving process. Data processing systems do not have the capabilities to generate flexible strategies.
2. *Spatial Decision Support Systems (SDSS)* are “interactive, computer-based systems designed to support a user or group of users in achieving a higher effectiveness of

[4] Liggett, Friendman, and Jepson. p. 1.
[5] Malczewski, 1999. pp. 278-309.

decision making while solving a semi-structured spatial decision problem."[6] SDSSs allow the user to make "better" decisions through modeling and exploration of the decision problem in a recursive fashion. The objective of SDSSs is to support the decision-making.

3. *Spatial Expert Systems (SES)* are used when all the relevant knowledge of an expert decision-maker can essentially be encoded and used to make the decisions. The general assumption of SESs is that non-experts can use the systems to improve their decision-making. The key characteristics of SESs are (1) capability of solving spatial problems as well, or better than the experts, (2) ability to integrate expert knowledge in the form of rules, and (3) interaction with decision-makers. While similar with SDSSs, the objective of SESs is more towards storing the expert knowledge in a system and "replacing" the decision-maker.
4. *Spatial Expert Support Systems (SESS)* are semi-structured and are an integration of SDSSs and SESs.

Various software companies have developed modeling, optimization and decision support software that link to GIS such as Automated Mapping/Facilities Management (AM/FM), Work Integration Manager, Spatial Analyst and Network Analyst. Table 2 provides a short list of commercially available GIS-pertinent software.

Other spatial support systems for different disciplines other than CIS have been developed for specific research/industry needs. Identifying the decision-making systems that have been developed and analyzing their capabilities and weaknesses will help to develop more efficient programs for decision-making in CIS.

*Table 2: Selected Spatial Decision Support Systems*

| Software | Description |
|---|---|
| AM/FM | Automated mapping and facilities management; used by utility companies to record and keep track of power lines, gas lines, valves, meters, and land |
| Work Integration Manager | Integrates GIS with network-oriented Work Management System (WMS) through plug-ins; consists of Work Request Administration, Work Request Design, Standards Maintenance and Systems Administration; graphic-based[7] |
| Spatial Analyst | Enables desktop GIS users to create, query, and analyze cell-based raster maps; derive new information from existing data; query information across multiple data layers; and fully integrate cell-based raster data with traditional vector data sources[8] |
| Business Analyst | Enables user to create and analyze market areas, analyze customer profiles, determine target population, create simple or complex ring analysis for locations, compute equal competition areas, produce detailed comprehensive reports[9] |

[6] Malczewski, 1999. p. 281.
[7] http://www.convergentgroup.com
[8] http://www.cmcus.com/catalog/arcviewsa.htm
[9] http://www.esri.com/software/businessanalyst/overview.html

*Table 2 (continued): Selected Spatial Decision Support Systems*

| Software | Description |
|---|---|
| Network Analyst | Enables users to solve a variety of problems using geographic networks (i.e., streets, highways, rivers, pipelines, electric lines, etc.) such as finding the most efficient travel route, generating travel directions, finding the closest facility, or defining service areas based on travel time[10] |
| TransCAD | Enables user to do network analysis, shortest path, transportation problem, spatial interaction, location-allocation, traveling salesman problem, and stochastic problems[11] |
| Utility Solutions 2000 | Integrates engineering, operations, planning, billing and SCADA[12] to offer support that addresses the operational phase of a utility; provides a set of AM/FM/GIS functions that include mobile mapping and staking, work orders, dispatching, engineering planning and integration with customer billing[13] |

## 5.0 Interoperability

Engineers often use computer-assisted drafting/drawing/design (CAD) to design new roads, sewers and water lines. Natural scientists and environmental engineers use various modeling software to determine groundwater flows or the spread of contaminants. Transportation engineers may use decision support systems to assist them in designing their transportation networks. Spatial information is displayed and analyzed through GIS, CAD, image processing systems, data processing systems, decision-support systems, and modeling software. Combining or linking two or more of these systems can greatly increase analysis and decision-making capabilities of the GIS. While many decision-making systems are GIS-compatible, this is not always the case for other systems. In situations where a combination of imaging processing systems, GIS and modeling systems are required, files and datasets are not always compatible.

Interoperability refers to the integration of systems and applications that were not originally designed to be integrated but are combined to address problems that require linked systems. Interoperability involves the exchange of data that have different

- Semantic representations (i.e., identification of type of data and how objects are represented)
- Spatial and temporal scales
- Formats
- Geospatial references (i.e., different projections, reference ellipsoids)
- Domains (i.e., how the world is viewed, named, defined, described, modeled)

Linking systems and having an “open interface” between them is a complicated problem that is being evaluated by the Open Geospatial Interoperability Specification Consortium

[10] http://www.esri.com/software/arcview/extensions/netext.html
[11] http://www.caliper.com
[12] SCADA – Supervisory Control and Data Acquisition
[13] http://www.uaintegrators.com

(OpenGIS or OGC). OGC is a not-for-profit organization that has engaged key user organizations and technology providers to "address the lack of interoperability among systems that process geo-referenced data."[14] OGC has drawn members from leading software, GIS, computer and telecommunications companies, organizations and universities such as AutoDesk, BellSouth, Compaq, ESRI, Hewlett-Packard, Intergraph Corp., Microsoft Corp., Massachusetts Institute of Technology, New York University, Raytheon Systems, University of Illinois, University of Muenster, University of Tokyo, FGDC, NASA, NIMA, National Science Foundation (NSF) and the Census Bureau. Through interactions with industries that use GIS, researchers and software developers become aware of how the industries perceive their data and the difficulties and interoperability problems that need to be addressed and resolved. Additionally, university members can use available commercial resources to improve their research techniques and be informed of improving technologies.

The University Consortium for Geographic Information Science (UCGIS) is another organization involved in solving the interoperability issue by bringing together specialists in various disciplines.[15] Both the UCGIS and OGC are seeking to unite the different geospatial industries and meet the needs of the marketplace (both in academia and industry). Since civil infrastructure systems are a large part of the geospatial industry, it will be important for key players to begin to understand their own interoperability and industry needs for current and future applications and cooperate with OGC and UCGIS to meet those needs.

## 6.0 Sources of Geospatial Data

One of the first difficulties encountered in creating a GIS is the collection of spatial data. For civil infrastructure systems, social and economic data can be hard to locate at the scale required. Much of the economic data from the Census Bureau is available at the national, state, and county level. Information at a local or city/town level is limited and often difficult to obtain. Below is a brief summary of the available data for the four elements of CIS.

*Demographic Data*

Demographic data are available from the Census Bureau decennial TIGER (Topologically Integrated Geographic Encoding and Referencing system) files. Available datasets include political boundaries (state, county, cities, congressional districts and school districts), voting and registration, census tracks and block boundaries, population, housing, income, race/nationality and household data. Table 3 contains a list of available data at the census tract level.

[14] OpenGIS Consortium, http://www.opengis.org
[15] UCGIS, http://www.ucgis.org

*Table 3: Typical Census Tract Data*[1]

| | | |
|---|---|---|
| Population | Place of Birth | Household Income |
| Urban and Rural distinction | Residence | Wage or Salary Income |
| Sex | Place of work | Social Security Income |
| Age | Employment status | Public Assistance |
| Race (White, Black, American Indian | Occupation | Retirement income |
| and Eskimo/Aleut, Asian or Pacific | Class of worker | Poverty Status |
| Islander, Hispanic, other) | Hours per week worked | |
| | Means of transportation | Tenure of Household |
| Household Type/Relationship | Travel time | Year structure built |
| Presence and age of children | Private vehicle occupancy | Year householder moved in |
| Family Type | Vehicles available | Units in Structure |
| Marital Status | | Bedrooms |
| | School enrollment | Kitchen facilities |
| Language spoken at home | Type of school | Source of water |
| English Proficiency | Educational Attainment | Sewage disposal |
| Ancestry | Veteran Status | House-heating fuel |
| Year of entry | Period of military service | Plumbing facilities |
| Age by citizenship | Work disability status | Gross Rent |

[1]Based on data available for Census Tract 5359 South Gate, Los Angeles, LA County (Population: 10495, Tract Area: 0.73 square miles)

The Public Use Micro Data Samples (PUMS) provides a survey data set based on the long form of the decennial census collection. The data available include ancestry, occupation, race, language, income, commute to work, year home was built, single/multi-family and length of residence. The County and City Data Book is available for 1944-1993 and is gathered from various federal agencies and national sources. The data include socioeconomic and housing data from the 1990 census and the surveys that update them, business in cities and counties, median income, tax base, elections and other variables for counties and cities nationwide. Crime reports are available at the county level from the United States Department of Justice – Federal Bureau of Investigation. Other demographic information is also available from both public and private sources that use the census data to produce interpolated and summarized data.

*Economic Data*

Economic data are available for businesses at national, state and county levels through the Census Bureau and the County and City Data book. Data are available on household income, housing value, retail trade, wholesale trade, service industries, manufacturing industries, mineral industries, construction industries, transportation, labor force, banking, government employment and finances. However, data below the county level is scarce and difficult to obtain due to issues of privacy. The Census Bureau is not permitted to release any data that can identify any individual person or business firm. However, the Census Bureau does allow qualified and responsible persons, determined through a strict application process, to pay a fee to access the data. The data cannot leave in its raw form but must be aggregated so that it does not disclose information about individuals and cannot be combined with other datasets to pinpoint individuals. Marketing firms typically produce commercially available economic data at a fine scale by interpolating the decennial census block data.

Data on land valuation can be purchased at the county Assessor's office but can be quite costly if a large area is required. Los Angeles County is currently in the process of producing a GIS-ready base map of all 2.3 million parcels in the county. Attribute data for each parcel is available. Not all parcels have been mapped in GIS, but hardcopies of the parcel boundaries are available.

*Data on the Natural Environment*

The US Geological Survey (USGS) and the Environmental Protection Agency (EPA) have extensive web resources that contain maps and datasets of the natural environment as well as useful links to other websites. The EPA Spatial Data Library System (ESDLS) and the National Spatial Data Infrastructure (NSDI) have powerful search engines that allow the user to find spatial data based on a variety of queries. Table 4 contains a listing of several main sources for both the natural and built environment.

*Table 4: Summary of Available Data on the Physical Environment*

| **Source** | **Data Available** |
|---|---|
| U.S. Geological Survey (USGS) | Boundaries<br>Hydrography<br>Manmade Features<br>Pipelines, Transmission Lines<br>Transportation Features, Railroads, Roads and Trails<br>Earthquake Maps<br>National Wetlands Inventory<br>Ecological Zones<br>Topographic Features (DEM, DRG)<br>Land Use (LULC)<br>Geographic names information system |
| Environmental Protection Agency (EPA) | Air Quality<br>Regulated Facilities Point Locations<br>Hazardous Waste Areas<br>Superfund Locations<br>Point and Non-point Sources<br>Water Quality |
| Natural Resources Conservation Service | Soil surveys (SSURGO)<br>State soils (STATSGO) |
| Census Bureau Tiger/Line Files | Boundaries (national, state, county, census tract and block)<br>Hydrography<br>Landmarks<br>Utility Lines<br>Roads, Railways |

*Data on the Built Environment*

The TIGER/Line files contain data on landmarks, transportation, and utility lines. The Dynamap/2000 database contains a comprehensive U.S. street and address database. Dynamap has also produced commercially available postal correspondence files that link zip code areas to census blocks. Data on buried infrastructure, such as sewer and water lines, are not as extensive since many pipe and cable networks either have not been digitized or are owned by utility companies. Detailed pipe and cable networks are not likely to be found on the web, but may be obtained from local governmental agencies.

Due to the proliferation of increasingly complex and diverse data sets, the Federal Geographic Data Committee (FGDC) has coordinated the National Spatial Data Infrastructure (NSDI). The NSDI seeks to set policies, standards, and procedures for organizations to produce and share geographic data more effectively. Goals and objectives of the NSDI include maintaining state of the art knowledge about new technologies and advances in geographic information, and building a comprehensive and user-friendly clearinghouse of free or affordable spatial data.

As GIS becomes more widely used, it becomes increasingly important to determine through key CIS personnel and organizations how and where advanced GIS can benefit the urban community. This will then lead to the development of a list of data sources to be collected, or produced if currently unavailable. Additionally, encouraging cities and counties to adopt GIS will improve efficiency in data gathering and sharing among governmental agencies.

## 7.0 Advanced GIS Applications

For each of the elements of the built infrastructure, various industries, academic/research institutions and software industries are developing models and solutions to better design and maintenance.

*Public/Private Buildings*

Since design and maintenance of the actual buildings are typically done for each individual building, GIS is most often used for locating optimal sites. This can be accomplished through buffering, overlaying and other methods. The availability of other infrastructure will also dictate where buildings are located. In the case of large industrial, commercial or residential developments, demographic forecasts, quality and quantity of infrastructure, transportation studies and urban planning strategies become increasingly important. Correlations between social and economic data and existing infrastructure could furnish insight into which areas to develop. Or similarly, new infrastructure can be constructed to encourage development in particular areas.

*Public Utilities (Cable-based and Pipeline-based)*

Public utilities include cable-based utilities such as electricity, telephone, Internet and television service. Pipeline-based utilities consist of steam, gas and liquid fuels, as well as water and wastewater services. The three major challenges facing the utility industry are "large service areas, many distributed customers and remotely distributed aging facilities."[16] AM/FM systems integrated with other emerging technology provide essential solutions for utility companies. AM/FM technology has capabilities for mapping process automation, record keeping, spatial analysis, and data/application integration. This technology allows utility companies to perform load and network analysis, keep records and report usage, map out their facilities, perform outage analysis, maintain and keep record of inventory, know customer location, usage patterns and service preferences, and perform marketing analyses.

Li, Coleman and Easa[16] have developed a list of specific applications of spatial analysis capabilities for selected utility sectors as shown in Table 5. Since utility companies are constantly expanding to meet customer needs and to draw in new customers, global positioning systems (GPS) have been integrated with handheld tools to assist in field data collection. Additionally, GIS Toolkits allow utility companies to create custom spatial applications to meet specific needs while supervisory control and data acquisition (SCADA) software manipulate equipment and allow real-time information to be gathered from remote locations. For example, SCADA is used in gas pipeline companies to model its network and collect real-time information on gas flow, pipeline pressure, sections under repair, alternative pipeline routings, as well as the location and dispatch of service crews.[17]

Another application of GIS is identifying areas for investments, mergers and acquisitions. Software such as Spatial Analysis (ESRI) is often used to determine parcels of land that may be beneficial for investment based on a number of queries (for example, in determining a location for a shop, parcels of land located close to or away from competitors and on major streets might be queried). A similar process might be used to determine areas that utility and infrastructure enterprises could acquire. A combination of demographic and economic data could identify areas where civil infrastructure may be over or under provided. Identifying potential investment areas, visualized through GIS and complemented by company information, can provide information to support decisions regarding mergers and acquisitions.

[16] Li, Coleman, and Easa, 2000. "Public Utilities," *Urban Planning and Development Applications of GIS.* Renton, Virginia: ASCE. p. 133.
[17] Ibid., 2000, p. 146.

*Table 5. Specific Spatial Analysis Applications for Various Utilities*[18]

| Utility | Spatial analysis applications |
|---|---|
| Electricity | Outage analysis (dealing with trouble calls)<br>Maintenance routing<br>Transmission line siting<br>Load pattern and growth analysis<br>Impact analysis in facilities siting |
| Water, wastewater, stormwater | Breakage and leakage diagnosing<br>Maintenance routing<br>Water network flow analysis<br>Modeling damage to water distribution systems<br>Water resources planning and management<br>Simulation of ground water mass destruction<br>Prediction of runoff rates<br>Flood control<br>Determination of pressure zone when planning new water distribution facilities |
| Steam, gas and liquid fuel pipelines | Breakage and leakage diagnosing<br>Maintenance routing<br>Modeling damage to gas distribution systems<br>Network optimization<br>Facilities siting<br>Earthquake simulation |
| Telephone/cable TV | Network/cable routing<br>Facilities siting and location optimization<br>Outage and performance problem analysis<br>Black spot/zone analysis in cable television |
| Telecommunications | Radio propagation and area coverage analysis<br>Optimum antenna heights and locations using DTM information<br>Optimal design of a broadband network layout<br>Analyzing tower coverage areas and service accessibility of a mobile communications network<br>Network traffic analysis by combing demography |

*Transportation (Highways, Bridges, Streets, Railroads, Mass Transit, Ports and Waterways, Air Transportation Facilities)*

Advanced GIS has been applied to the transportation field in network design/analysis, scheduling (public transportation, freight), routing (maintenance, waste transport), traffic control and inventory, safety analysis (crash location and analysis), intelligent transportation system (in-vehicle navigation, emergency response, commercial vehicle transport, traffic management), and site impact analysis (increased traffic, air quality, noise pollution).

Social and demographic data is vital in designing effective transportation systems and justifying their construction and capacity. In Baltimore, for example, transit demand and

[18] Li, Coleman and Easa, 2000, p. 138. (Electricity, Water, Telephone/cable TV, Telecommunications)

demographic forecasts for a new light rail system were imported to a GIS for spatial analysis and color displays for senior management. [19] Census data such as transport taken to work, departure, and travel time to work are particularly useful.

One of the key GIS activities specific to transportation is network analysis. Since these networks are used for routing and emergency dispatch, high-quality data with accurate information on the connectivity of the system, such as turning options at intersections, and capacities and demands on the system, is required. Missing or incorrect data about the system can be a serious problem, particularly in an emergency situation. [20] Having an accurate and updated transportation GIS not only aids in its management but also allows for other organizations and governmental departments to utilize the data for other uses such as routing for utility maintenance, facility siting and tourism.

*Solid waste disposal (landfills, ocean disposal, recycling facilities)*

Crucial uses of GIS for solid waste disposal are facilities siting, vehicle routing, and landfill design and management. Facility siting criteria include proximity to residential areas, environmental effects, soil and geological properties, cost of land and distance from collection sites. GIS overlay, buffer and distance calculations can greatly improve facility siting, as well as provide a valuable tool for producing key maps for concerned citizens.

GIS has been used to assist landfill design and management by inputting topographic and features data in order to estimate the geomembrane and clay required, locate gas and leachate pipes, determine required pipe lengths, record waste composition and compaction, evaluate the potential for gas migration, analyze the chemical and physical stability of the site over time, and recommend and analyze the filling process to maximize capacity while minimizing environmental impacts.[21]

Linking GIS with models of groundwater flow and contaminant migration may also be useful for evaluating older landfill sites or determining environmental risks associated with the presence and migration of hazardous substances.

*Other CIS Related Fields*

Since CIS involve a range of fields, it is valuable to be aware of the different research areas that are being pursued that may be relevant to advanced GIS application in civil infrastructure systems. These include:

*Social Sciences* – An effort to collect and make available social and economic data is evident in the presence of data clearinghouses such as the Inter-university Consortium for Political and Social Research (ICPSR) and the Cornell Institute for Social and Economic

[19] Souleyrette, R. and Strauss, T., 2000. "Transportation," *Urban Planning and Development Applications of GIS.* Renton, Virginia: ASCE. p. 121.
[20] Souleyrette and Strauss, 2000, pp. 118-119
[21] Green, 1996.

Research (CISER). Correlations with social and economic data and the quality and quantity of infrastructure could provide understanding into where to install new utility networks or how cities and counties can better plan for new infrastructure based on population growth. Acquisition of data on behavioral patterns in utility usage and spending would be of great value to utility companies.

*Urban planning* – GIS is widely used in urban and regional planning. Existing GIS on land use, growth planning, and real estate valuation are essential in determining where and when to develop new areas. By working hand in hand with urban planners, governmental agencies and utility companies can better plan for maintenance of existing infrastructure and construction of new facilities.

*Weather and natural disasters* – Through modeling techniques, researchers are more able to locate areas that are vulnerable to earthquakes, hurricanes, typhoons, floods and forest fires. Satellite imagery and other remote sensing technology are also valuable in understanding weather and natural disaster behavior. This knowledge is critical for improving decisions concerning emergency response, planning, and design.

*Environmental Quality* – Using air and noise pollution modeling, the effects of highways, railroads and airports can be assessed during the design phase. Waterways and water resource modeling can assist hydrologists in locating water sources and designing more intelligent water distribution systems. GIS information on the spread of pollutants can also shed light on areas that would be more costly to install infrastructure, or areas that may require additional maintenance.

It is important that researchers and professionals in civil infrastructure systems are aware of the improving technologies and techniques for infrastructure development. Additionally, they must also be familiar with other relevant research fields and GIS improvements. Encouraging inter-disciplinary and multi-disciplinary cooperation can greatly increase the knowledge base for improving civil infrastructure.

## 8.0 Remote Sensing and Time-dependent Information

An additional aspect of GIS that is gaining widespread attention is the temporal feature of spatial data. Time-dependent data come into use for monitoring purposes, maintenance, economic planning and tracking emergency, post-disaster situations.

For monitoring purposes, remote sensing technologies and global positioning systems (GPS) that are linked to GIS are used to track various types of infrastructure such as 1) traffic monitoring through the use of cameras and image processing to determine the speed of traffic and accidents that occur 2) postal/cargo tracking using GPS, and 3) pipeline monitoring through sensors placed on pipelines to determine amount of flow. Remote sensing technologies have the potential of identifying problem areas before the situation becomes very costly, such as in the case of gas pipe leakage or water leakage.

With a link to GIS, the temporal information collected can assist in maintenance and emergency procedures.

To pinpoint locations of structures or positions relative to a map, GPS has been extremely valuable. Typical GPS units can determine a location within a few meters of their actual position while more sophisticated GPS can be accurate within centimeters. GPS technology was utilized after the 1999 Kocaeli earthquake in Turkey to determine the location of certain streets and damaged buildings. The data were collected from the satellite in real time as the researchers inspected the damaged area. The GPS was linked to a GIS which allowed the data to be mapped immediately to assess the severity and impact of the earthquake.[22]

Another form of remote sensing is the use of imagery – satellite and radar imagery and aerial photography. This has been used in emergency, post-disaster situations when satellite imagery and global positioning systems (GPS) were used to track and locate damaged areas. With satellite imagery able to achieve resolutions of 1m, damage from earthquakes, floods, and other natural disasters can be estimated from these images. However, it must be noted that the effective use of imagery is highly dependent on interpretation. These technologies have been applied to earthquakes in Kobe, Japan and Luzon, Philippines (Matsuoka, Yamazaki, 2000). Matsuoka and Yamazaki examined Landsat and synthetic aperture radar (SAR) imagery before and after the earthquakes to determine whether damage to buildings and other structures can be extracted from the imagery. It was found that damaged buildings are often darker in radar images than the images of their undamaged states. For the Luzon earthquake, satellite imagery taken before and after the earthquake were used to delineate areas that had subsided into the sea.

Due to the variability in resolution and the need for interpretation, satellite, radar, and aerial imagery are more valuable for sensing relatively large changes above ground. This information can indicate areas where infrastructure should be checked for damage and can help determine how to evacuate people from dangerous locations. The use of remote sensors and GPS, which can be more accurately controlled, will be valuable in monitoring infrastructure quality on a day-to-day basis.

## 9.0 Recommendations

To improve the planning and rehabilitation of civil infrastructure systems through GIS, a national forum is proposed to engage GIS experts from industry, government and academia as well as leading companies, consultants and universities involved in civil infrastructure systems. This forum will seek to meet the following objectives:

1. Gather information on current GIS uses, research and development and compile a list of relevant data sources available

[22] Eguchi et al, 2000.

2. Determine the specific needs of the civil infrastructure systems community that can be met by GIS
3. Explore plans for future research and brainstorm new applications for GIS
4. Determine the issues that need to be resolved in order to accomplish the current and future applications including increasing GIS capabilities, interoperability issues, remote sensing technologies and data sources not currently available
5. Engage GIS and other systems software developers and researchers to begin to resolve the issues

As the applications and possibilities of advanced GIS are realized, the maintenance and planning of civil infrastructure systems will be greatly improved. Greater understanding of the capabilities of related systems will refine the decision-making process in civil infrastructure systems.

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Data Sites

ArcData Online (links to Dynamap/2000) http://data.esri.com/
Environmental Protection Agency (EPA) http://www.epa.gov
FEDSTATS http://www.fedstats.gov
National Imagery & Mapping Agency (NIMA) http://www.nima.mil
Open GIS Consortium (OpenGIS/OGC) http://www.opengis.org
The Digital Chart of the World http://ilm425.nlh.no/gis/dcw/dcw.html
The Federal Geographic Data Committee (FGDC) http://www.fgdc.gov/
U.S. Bureau of Reclamation http://www.usbr.gov, http://www.rsgis.do.usbr.gov
U.S. Census Bureau (TIGER/Line) http://www.census.gov
U.S. Department of Energy (DOE) http://www.doe.gov
U.S. Federal Bureau of Investigation (FBI) http://www.fbi.gov/homepage.htm
U.S. Geological Survey (USGS) http://www.usgs.gov

Search Sites

Cornell Institute for Social and Economic Research (CISER)
http://www.ciser.cornell.edu
Columbia University Electronic Data Service (EDS) http://www.columbia.edu/acis/eds
EPA Spatial Data Library System http://www.epa.gov/enviro/html/esdls/esdls_over.html
Inter-university Consortium for Political and Social Research (ICPSR)
http://www.icpsr.umich.edu
North Carolina Library http://www.lib.ncsu.edu/stacks/gis/dataweb.html
National Spatial Data Infrastructure (NSDI) http://mapping.usgs.gov/nsdi
Spatial Odyssey, GIS Literature Database http://wwwsgi.ursus.main.edu/gisweb/
Urban and Regional Information Systems Association (URISA) http://www.usrisa.org
University Consortium of Geographic Information Science http://www.ucgis.org
US GEOData – http://edc.usgs.gov/doc/edchome/ndcdb/ndcdb.html