

iDEN allows an MS user to roam freely to any connected system and maintain full telephone interconnectivity (including circuit-switched data) and short messages, provided such services have been contracted for with the originating service provider. iDEN circuit-switched data are designed to be compatible with the following applications:

1. Laptop and palmtop computers;
2. Fax and image processing;
3. File transfer and other "dial-up" applications;
4. One-to-one connections between an in-vehicle user device and the PSTN.

iDEN circuit-switched data are compatible with the Radio Link Protocol (RLP) and full-duplex packet stream. In addition, MS users have the ability to receive short alphanumeric messages on their MS displays. A short message is generated by the Short Message Service-Service Center (SMS-SC). High-speed packet data service is being planned. Furthermore, iDEN provides system control with an authentication mechanism, which may be invoked prior to any chargeable service initiation. Clearly, iDEN can be used for placing various vehicle communication applications on a single bill since it is provided by a single nationwide service.

8.3.5 Radio Data Networks

The operational principle of radio data networks (RDNs) is similar to that of cellular networks except that RDNs are dedicated to data and are not circuit switched. RDNs consist of land-based radio base stations and efficient switching networks for packet data. Cellular-like frequency reuse and overlapping cells allow users to roam seamlessly. The network communication protocols either conform to the ISO Open Systems Interconnection (OSI) Reference Model (shown later in Figure 8.10) or the Internet protocols, which enable efficient interconnection and data transmission among all components of the network.

The growth of RDNs has been limited by the availability of unassigned radio spectrum. Although other widespread networks are in the planning phases, only two major RDNs are currently operating in the United States: ARDIS and RAM Mobile Data. These networks have been allocated frequencies in the 800- and 900-MHz bands and provide wireless packet data services to a large number of subscribers. Recently, several CDPD networks have been deployed and extended to selected cities where circuit-switched data services are used to send the packets to the CDPD network. Table 8.7 provides an overview of these and other networks. The Ricochet RDN shown in Table 8.7 was developed by Metricom, Inc., and uses the unlicensed 902- to 928-MHz band. It claims to be faster than the ARDIS and RAM Mobile Data networks. Further information on this and another proposed network can be found in [1,22].

Table 8.7
Radio Data Networks

Network	Gross Data Rate	User Data Rate	Frequency	Data Protocol	Modulation	Channel Access	Channel Spacing	Modem
ARDIS	4.8 or 19.2 Kbps	2.4 or 9.6 Kbps	800-MHz band	MDC- 4800 RD-LAP	FSK	FDMA/ DSMA	25 kHz	ARDIS, IBM, Motorola
RAM (Mobitex)	8 Kbps	4 Kbps	900-MHz band	MASC IP	GMSK br=0.3	FDMA/ S-ALOHA	12.5 kHz	Ericsson, IBM, RIM, Megahertz, Motorola, etc.
CDPD	19.2 Kbps	9.6 Kbps	800-MHz band	TCP/IP PPP/SLIP	GMSK	FDMA/ DSMA	30 kHz	Cincinnati Microwave, Sierra Wireless, PCSI, etc.
Ricochet	76 Kbps	19.2 Kbps	902-928 MHz	TCP/IP	GMSK	FH SS (ISM)	160 kHz	Metricom, Inc.

ARDIS

One of the first RDNs to be established in the United States, ARDIS grew out of a private wireless data network that Motorola had built to support IBM's nationwide staff of field technicians. In 1990 the network made its services publicly available to business firms needing to stay in touch with mobile workers. ARDIS now has more than 60,000 end-users in 400 metropolitan areas and 10,700 cities and towns across the United States. This network is typically used to support two-way data transfers of less than 10K in size. The maximum packet size is 240 bytes (not including the 16-bit address field). Remote users can access the network via handheld or laptop computers with radio modems that communicate with the base stations. Each base station is connected to one of 32 radio network controllers managed by two ARDIS hosts. These hosts, as access points, are linked to the customers' mainframe computers via leased telephone lines using asynchronous, SNA LU6.2, or X.25 dedicated circuits.

The ARDIS network architecture is cellular-like with overlapping cells. The base station provides line-of-sight coverage up to a radius of 16.09 to 24.14 km (10 to 15 miles). ARDIS can support portable communications from inside buildings and on the street because of the overlapping coverage, designed power levels, and error-correction coding in the transmission format. ARDIS has between one and three duplex pairs in each of its service areas. Each duplex channel has two 25-kHz channels spaced 45 MHz apart. ARDIS supports data transmission rates of up to 4.8 Kbps using its equipment (MDC-4800) and 19.2 Kbps on upgraded equipment (RD-LAP), for a maximum user data rate of about 8 Kbps.

Both host routing and peer-to-peer messaging options are available. Host routing is used when a wireless device sends messages to and receives messages from a fixed host connected to the ARDIS network. This method of routing is suitable for applications that require central control functionality or interoperability with other networks and fixed systems and is usually accomplished using a dedicated private line operating under the X.25 PTP protocol. Peer-to-peer routing supports exchange of messages between individual wireless devices. These messages are routed to the destination wireless devices by the ARDIS network.

RAM Mobile Data

The RAM Mobile Data network is based on the Mobitex system developed by Ericsson in Sweden. RAM operates the Mobitex network throughout the United States, covering more than 7,700 municipalities, including airports and major transportation corridors. More than 40,000 subscribers currently use RAM's service for applications including field transportation, field service, field sales, finance, utilities, telemetry, point-of-sale transactions, public safety, and messaging.

The RAM network is hierarchical in structure, with the network control center, which manages the entire network, forming the top layer. National switches, which route traffic between service regions, form the next layer (immediately below the network control center). The next two layers are occupied by regional switches and local switches, each of which handles traffic within a given service area. The base stations, which communicate with the mobile and portable data devices, are at the bottom. The host computers are connected at the local switch layer using standards such as X.25, TCP/IP, SNA LU6.2, and SNA 3270, with speeds of up to 64 Kbps. RAM provides an interconnected trunked radio network that is configured like a cellular phone system, except that hand-offs are managed by the mobile terminal itself rather than the network.

The RAM network has 10 to 30 two-way radio channels with a bandwidth of 12.5 kHz in each metropolitan service area. Its hierarchical architecture enables RAM to route messages via the shortest available path for increased speed and reliability. Data are sent between devices in the field and the base stations over the air at 8 Kbps in half-duplex mode with a maximum file size of 20K and a user data rate of 4 Kbps. The maximum packet size is 512 bytes (not including the 24-bit address field).

Cellular Digital Packet Data

Cellular digital packet data (CDPD) is a fast, efficient, digital data transmission system that overlays existing analog cellular networks. The system operates at 19.2 Kbps per channel and internetworks with existing data networks based on ISO 8473 (CLNP) or the Internet Protocol. CDPD provides maximum connectivity by using idle times between cellular voice calls or by transmitting in a dedicated-channel environment.

Some people believe that CDPD should be gaining prominence over other land-mobile-radio data technology because of the following. CDPD is designed to be reliable and secure. CDPD's data transmission technology is efficient, using the bandwidth not utilized by voice. CDPD utilizes much of the cellular infrastructure currently in place for the voice network, allowing for quick implementation and reduced network costs. CDPD's open network design approach permits technological evolution and service extensions. Recently, the U.S. Joint Architecture Team for national ITS selected CDPD as the preferred network for providing traffic and route guidance information to motorists [23].

CDPD operates on a network that consists of the basic components shown in Figure 8.5. Mobile End Systems (M-ESs) are portable subscriber devices that permit the user to gain access to the network by sending and receiving CDPD radio signals. Mobile data base stations (MDBSs) are located within each cell site and act as a data relay between the M-ES and the MD-IS (see remainder of paragraph). The

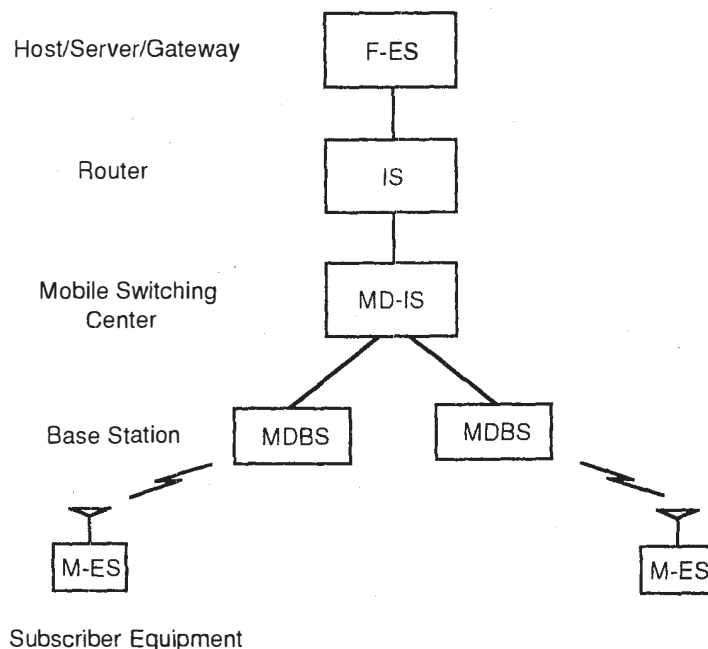


Figure 8.5 CDPD network.

MDBS communicates with the MD-IS via a 56-Kbps data link. The Mobile Data Intermediate System (MD-IS) performs routing functions based on its knowledge of which M-ESs are in its service area. The Intermediate System (IS) acts as a router, which completes the connection between the MD-ISs and the Fixed-End Systems (F-ESs) by making complex routing decisions and supporting data links as they change over time. The F-ES is equivalent to the traditional data application or internal network support and service application. Its location is geographically fixed. A F-ES is equivalent to a host, server, or gateway that can connect to public data networks, corporate customer networks, or the Internet.

The primary new technological components introduced by the CDPD network involve the use of existing cellular channels for air data link services and mobility management. The use of existing cellular channels for air data link services required introduction of the CDPD Airlink Interface. This specification defines all procedures and protocols necessary to allow efficient use of cellular channels for data communications.

Mobility management satisfies the requirement to provide continuous communications to mobile data subscribers. The CDPD System Specification defines procedures and protocols necessary to ensure correct and efficient delivery of

connectionless data packets between end systems. Connectionless network service enables the CDPD network to provide simple, reliable cell-transfer mechanisms. End-to-end connections are maintained by the mobile system and the application service provider.

With more than 16,000 AMPS cell sites existing in North America, CDPD has better potential nationwide subscriber coverage than competing packet-data wide-area networks, provided special CDPD equipment is available. It also has a high active user capacity. However, CDPD has some weaknesses. There is additional infrastructure cost to run voice and data side by side. Voice is given priority over data and may cause blocking of data services. The idle channel quality and foreign carrier detect features will cause CDPD to interfere with voice systems. To date, CDPD has not been widely deployed—it has seen much less than ARDIS in the United States. Only time will tell if CDPD can overtake ARDIS and RAM. Refer to [24] for more information on CDPD.

In conclusion, both ARDIS and RAM were developed for applications involving short wireless messages. Currently, Ricochet has limited mobility support so most of its applications use wireline modems. Ricochet may not be suitable for mission-critical applications because it uses unlicensed bands and must yield to licensed users whenever there is interference. At present, it has less coverage than either ARDIS or RAM. Finally, CDPD has the potential to provide the largest coverage. The recently developed Circuit-Switched CDPD Specification enhances the coverage by allowing mobile devices in areas of no CDPD coverage to dial in and access a CDPD MD-IS. CDPD is suitable for applications requiring wireless short messages, burst messages, or lengthy sessions that can afford sporadic communications.

8.3.6 Broadcast Subcarriers

Broadcast subcarriers can provide voice or data communications from a broadcast station or infrastructure to vehicles without requiring a specially allocated frequency spectrum. Multiplexed subcarrier technology was first introduced in the 1930s when FM was invented by Armstrong [25]. The very name *subcarrier* implies that it is not the main signal carrier generated by a broadcast station. Instead, it is a radio signal (voice or data) broadcast along with the main signal on a sideband frequency assigned to a specific station because the main signal does not occupy the entire allocated spectrum. Although this technology was developed concurrently with FM, subcarrier signals can also be broadcast with amplitude modulation (AM) and television signals. In early days, any such signal transmission required a Subsidiary Communications Authorization (SCA). Even though the SCA was phased out in 1983, people still refer to these signals as SCAs. Traditionally, subcarriers have been used for a variety of subscription services: background music, weather forecasts, sports events, stock quotations, foreign-language soundtracks, special time signals, or other

information relevant to business, professional, educational, or religious interests, etc. Special receivers are required to listen to these signals. Recently, subcarriers have become very popular for broadcasting traffic information.

There are two broadcasting technologies. In monophonic broadcasting, only one audio signal is transmitted. Only one speaker is required to reproduce this type of signal. In stereophonic broadcasting, two audio signals are combined and transmitted over a single channel. A stereophonic receiver can separate the two signals to reproduce the original signals via separate speakers. A monophonic receiver may also receive and reproduce the stereophonic signals, but the spatial distribution effect will be lost.

As mentioned earlier, since all broadcast stations (AM, FM, and TV) have the ability to transmit subcarriers, they provide an effective solution for broadcasting traffic information. Subcarriers can transmit both audio and digital information side by side on the same channel in such a way that listeners with conventional receivers cannot hear the digital transmissions on the data subcarrier. Special receivers are required to access the data part of the channel. Table 8.8 shows some of the technical performance parameters of various subcarrier options (from the FCC: 47 CFR 73.319, [26,27]). AM subcarrier broadcasting is rarely used because of the relatively slow speed (10 to 12.5 bps), but higher data rates (up to a few hundred bits per second) are possible [28]. Note that in Europe and Asia (regions 1 and 3) the frequency allocated for each AM channel is only ± 9 kHz around the main carrier instead of ± 10 kHz (20 kHz total) for the United States (region 2).

As an example, FM radio stations can support a standard background music subcarrier audio (SCA signal) in addition to an analog audio channel with a frequency response from 50 Hz to 5 kHz. Since there is room for two such channels on a

Table 8.8
Technical Performance Characteristics of Subcarriers

<i>Station Type</i>	<i>Subcarrier Bandwidth</i>	<i>Injection</i>	<i>Main Channel Loss</i>
AM	None	None	None
monophonic			
AM	0–12.5 Hz (25 Hz)	5%, –32 dBc,	0 dB
stereophonic	(20 kHz)*	$\pm 2.86^\circ$	
FM	79 kHz	23.5 kHz	2 dB
monophonic	(20–99 kHz)		
FM	46 kHz	15 kHz	1 dB
stereophonic	(53–99 kHz)		
TV	104 kHz	50 kHz	0 dB
monophonic	(16–120 kHz)		
TV	73 kHz	25 kHz	0 dB
stereophonic	(47–120 kHz)		

*Total bandwidth occupied by the transmitted composite signal.

stereophonic FM carrier—one centered at 67 kHz and the other at 92 kHz, two data channels can be supported. Each channel can support up to 4.8 Kbps of data throughput without any impact on the station's audio quality. Several systems attempt to take advantage of this data capacity, such as the Secondary Audio Program (SAP) and PROfessional channel (PRO), the Vertical Blanking Interval (VBI) system, DARC (which was developed by NHK), HSDS (which was developed by Seiko), STIC (which was developed by MITRE), and the RDS/RBDS standards (which are discussed below). These systems are all listed in Table 8.9.

Radio Data System

The radio data system (RDS) was first defined by the European Broadcasting Union (EBU) and various European broadcasters, notably Swedish Telecom Radio (STR) and the BBC. Development of this system has been facilitated International Radio Consultative Committee (CCIR) Recommendation 643. Car radios that implement RDS first became available in 1987, and CENELEC (European Electrotechnical Standards Organization) is developing a standard for RDS receivers. The main purpose of RDS is to facilitate automated tuning by using data labels to identify the data segments being broadcast to RDS receivers. RDS uses an inaudible data-modulated subcarrier, added to the stereo multiplex signal from conventional FM broadcast transmitters. One of the first data-modulated subcarrier systems of this type was the MBS (mobile search) paging service, which was developed in Sweden by STR. MBS provided the initial basis for the system that became the EBU's RDS, and there are many similarities in the basic data transport system. From about 1976, development work on RDS was coordinated by a group of technical experts working under the auspices of the EBU. The specification was unanimously approved by all EBU members in 1983 and was published as EBU Technical Document 3244 in 1984. The following high-level requirements were established:

1. RDS signals must be downwardly compatible; they should not cause interference to reception of main program audio signals on existing receivers or

Table 8.9
Broadcast Subcarrier Systems

<i>Systems</i>	<i>Station</i>	<i>Status</i>	<i>Interface</i>	<i>Gross Data Rate</i>	<i>User Data Rate</i>
DARC	FM	Operational	Proprietary	19 Kbps	8 Kbps
HSDS	FM	Operational	Proprietary	19 Kbps	7.5 Kbps
RDS/RBDS	FM	Operational	Open	1.187 Kbps	≈0.3 Kbps
SAP & PRO	TV	Operational	Open	0.3–9.6 Kbps	0.3–9.6 Kbps
STIC	FM	Concept	Proprietary	18.8 Kbps	7.6 Kbps
VBI	TV	Operational	Open	1.2–19.2 Kbps	System dependent

interfere with the operation of receivers which use the ARI (Autofahrer Rundfunk Information) system (assist in tuning and alert the driver of imminent broadcasting).

2. The data signals should be capable of being reliably received over a coverage area at least as great as that of the main program signal.
3. The usable data rate provided by the channel should support the basic requirements of station and program identification, and provide sufficient scope for future development.
4. The message format should be flexible to allow the message content to be tailored to meet the needs of individual broadcasters at any given time.
5. The system should be capable of being reliably received on low-cost receivers.

Under the EBU RDS specification, a broadcaster can choose a subcarrier level such that the deviation relative to the subcarrier frequency is between 1 and 7.5 kHz, with a 2-kHz deviation recommended for most circumstances. A 57-kHz subcarrier is generally chosen (Figure 8.6) because it is a harmonic of the 19-kHz pilot tone. This subcarrier is suppressed and amplitude modulated by the shaped and biphase-coded data signal.

The RDS signal is transmitted as a biphase-coded signal with a data rate of 1187.5 bps. Along with the specified 100% cosine roll-off filtering, this provides an overall bandwidth of approximately 4.8 kHz for the data signal. The signal consists of 16 possible data groups as listed in Table 8.10. Like most serial data transmission systems, RDS partitions each data group into blocks: four blocks for

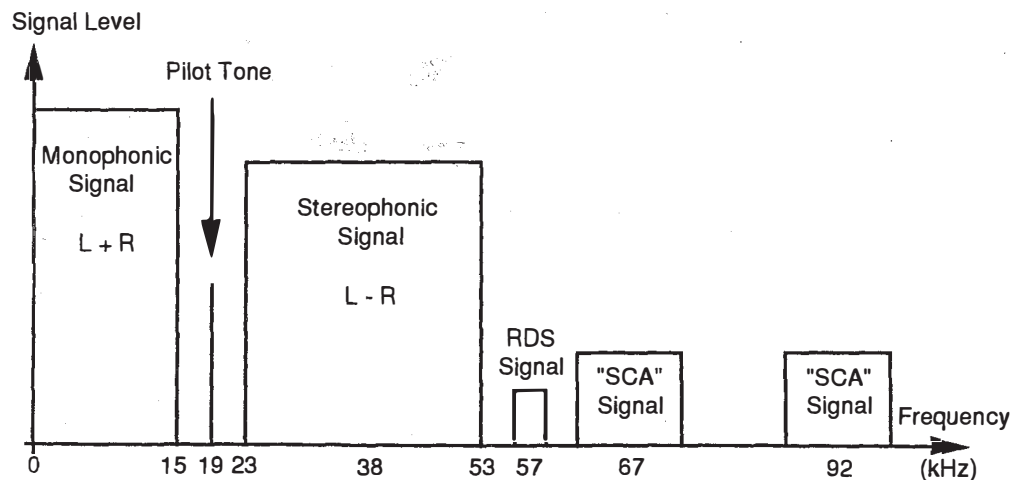


Figure 8.6 Spectrum of a FM stereophonic multiplex signal with RDS and SCAs.

Table 8.10
RDS Data Groups

<i>Group Type</i>	<i>Functional Description</i>
0	Basic tuning and switching
1	Program item number
2	Radio text
3	Location and navigation
4	Clock time and data
5	Transparent data channels
6	In-house applications
7	Radio paging
8	Traffic message channel (TMC)
9	Emergency warning
10	Program type name
11	Undefined
12	Undefined
13	Undefined
14	Other enhanced networks
15	Fast tuning and switching

the longest (104-bit) group. Each block has a 16-bit data word and a 10-bit checkword formed with a cyclic code shortened by burst error correction. The 10-bit checkwords are modified by various offset words to form a self-synchronizing code. On the frame receiving side, the decoder uses this self-synchronizing code to identify the beginning and end of the received data [29]. In other words, the checkwords in the burst-error-correcting code are used to indicate correct block synchronization and address the contents of each block. This code enables the decoder to reliably acquire synchronization within a one block period. The decoder obtains both block and stream synchronization using the different offset words contained in each of the four blocks that make up each group. The group type is embedded in the first 4 bits of the second block in each group. The fifth bit indicates the RDS version number, either A (value 0) or B (value 1).

A mixture of either fixed or variable RDS groups may be transmitted (in any order). The group format can be carried over from one minute to the next in order to meet different requirements at various times of day. The purpose of this mixture of fixed and variable format is to provide rapid access to tuning data while retaining the flexibility to allocate capacity to various applications to meet the different needs of individual broadcasters at any given time. If the required capacity is available, new group types can be placed into the transmitted data stream without affecting the operation of existing RDS receivers.

Although traffic information is very popular with European drivers, there is evidence that too many messages detract from satisfaction and make it very difficult

for broadcasters to handle. This service has been transmitted silently on FM under group type 8A (see Table 8.10—note that A is the version number), although it is not yet widely used. Other information, including emergency, weather, and radio programming information, can be displayed in textual format. In an effort to standardize the service provided by the traffic message channel (TMC), European countries have attempted to define the RDS-TMC service more completely and guide its implementation. More information about this coordinated effort can be found in [30].

Radio Broadcast Data System

The Radio Broadcast Data System (RBDS) is an outgrowth of RDS, and was developed by the National Radio Systems Committee of the United States under the sponsorship of the Electronics Industry Association and the National Association of Broadcasters. During development of the standard, an attempt was made to keep the RBDS standard compatible with RDS. However, a number of modifications had to be made because of the different structure of the broadcasting industry in the United States. RBDS turns out to cover both AM and FM broadcasting (while the European version only covers FM broadcasting). Although RBDS is a modification of RDS, it fully includes RDS. Therefore, the operational principles and data groups described in the last section are all valid under RBDS as well.

There are few only differences between RBDS and RDS [31]. RBDS includes an option for multiplexing RDS with the slightly modified MBS developed by Cue Paging. It also includes an option to use an in-receiver database permitting some sort of RDS functionality for AM and FM stations that do not implement RDS. RBDS has an option to add a yet to be defined AM data system. A few new concepts have been added, such as group type 3A being reserved for differential GPS (DGPS, Section 3.4.2), channels 0 and 1 of group type 5 being reserved for the in-receiver database system updates, and channel 2 being reserved as an SCA switch. The DGPS pseudorange correction data are sent by the reference stations using the RTCM SC-104 (Radio Technical Commission for Maritime Services Special Committee 104) industry-wide standard.

As we see from this section, RDS/RBDS technology can provide traffic, emergency, and weather broadcast features (in addition to news and entertainment) at the touch of a button, provided the user uses an RDS/RBDS receiver (radio). This explains why this broadcast subcarrier technology has become very popular in Europe and why it is now available for dynamic navigation systems in Japan (VICS, Section 10.3.2). The RDS and RBDS standards can be found in [32] and [33], respectively. More information about other broadcast systems using various subcarrier technologies can be found in [23,27,34].

8.3.7 Short-Range Beacons

Short-range beacons are a way of supporting vehicle-to-roadside communications. Beacons provide short-range communications and can transfer data at high speeds using a limited spectrum. Depending on the design, beacons can be used for one-way periodical broadcasting, two-way broadcasting and receiving, or two-way point-to-point communications. Besides vehicle location and navigation, beacons can also be used in many other applications such as electronic (automatic) toll collection, automatic vehicle identification, commercial vehicle operations (CVO), traffic management, and vehicle-to-vehicle communications. Several recent examples involving the application of this technology to vehicle location and navigation can be found in Section 10.3.

Either microwave or infrared beacons can be used. In Europe and Japan, microwave beacons operate in the 2.5- and 5.8-GHz bands [35–38], and infrared beacons operate at wavelengths of 850 and 950 nm. CEPT has assigned space in the 63-GHz band for development of vehicle-to-vehicle communications. In the United States, although the 915-MHz band is more popular in products, the FHWA is preparing a petition to the FCC for allocating 5.8-GHz band for ITS applications. Table 8.11 provides a comparison of three beacon technologies available in the United States (after [23]).

There are three types of vehicle-to-roadside beacons: (1) location beacons, (2) information beacons, and (3) individual communications beacons [39]. Location beacons transmit signals identifying their location, map coordinates, road segment heading, and beacon number. Information beacons transmit both location signals and relay current road and traffic information received via cable. Individual communication beacons are used for two-way communications with vehicles. These beacons can be used to collect traffic data and guide the vehicle.

As it passes a communication beacon, an appropriately equipped vehicle can transmit measured travel times and waiting times experienced at traffic lights via the beacon to a centralized host. Meanwhile, it can receive relevant location and guidance information back from the beacon. For example (see Figure 8.7), each

Table 8.11
Short-Range Beacon Characteristics

<i>Manufacturer</i>	<i>System</i>	<i>Range</i>	<i>Data Rate</i>	<i>Transmit Block Size</i>
Hughes	Active RF	61m (200 ft)	550 Kbps	512 bits
Amtech	Passive RF	23–30m (75–100 ft)	300 or 600 Kbps	128 bits
Siemens	Infrared	60–80m (197–262 ft)	125 Kbps	256 bytes (downlink) 128 bytes (uplink)

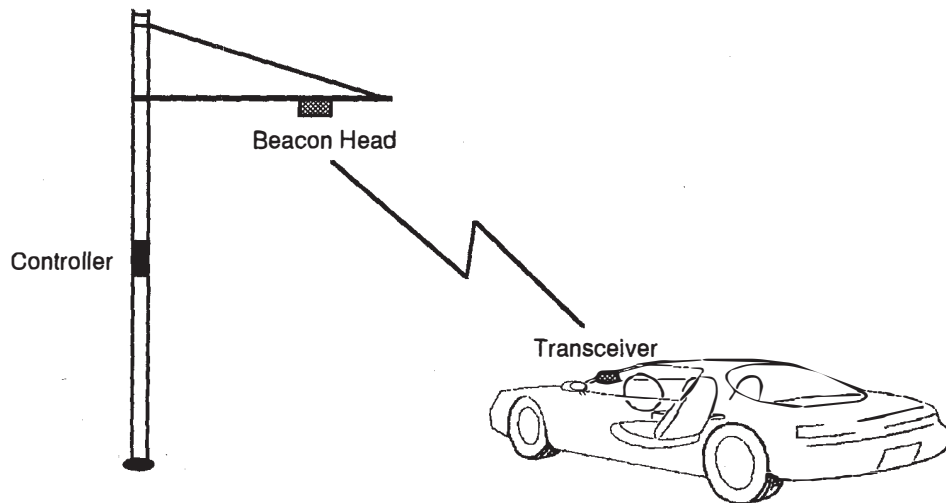


Figure 8.7 Beacon communication.

infrared beacon site in the EURO-SCOUT system (described in Section 10.3.1) consists of a beacon controller and up to 16 beacon heads that can be installed on road facilities such as sign posts, traffic lights, and poles [37]. Depending on the applications, beacon controllers and heads could be installed at every intersection, at every fourth traffic light, etc.

Figure 8.8 shows the relationship between the number of infrared beacon heads required, the transmission data rate, and the vehicle travel speed. These results are based on transmission data rates of 500 Kbps (downlink) and 125 Kbps (uplink) with a BER of 10^{-7} . One interesting observation is that the increase in the size of the region covered is proportional to the square root of n , where n is the number of beacon heads.

Beacon systems typically use dedicated short-range communication (DSRC) protocols. The main organizations working on DSRC standards are the European Committee for Standardization (CEN) incorporating with the ISO [40] and the American Society for Testing and Materials (ASTM) [41]. Similar to the digital map database standard, there is still no universally agreed upon DSRC standard available. Although international compatibility among beacon systems remains limited, many agree that the new standards must support multiple applications, be open to further evolution, be developed within a short time frame, ensure privacy and security, and be independent of such communications media as microwave and infrared.

One asynchronous protocol proposed in Europe and one synchronous protocol used in North America may be used as examples. The asynchronous protocol is

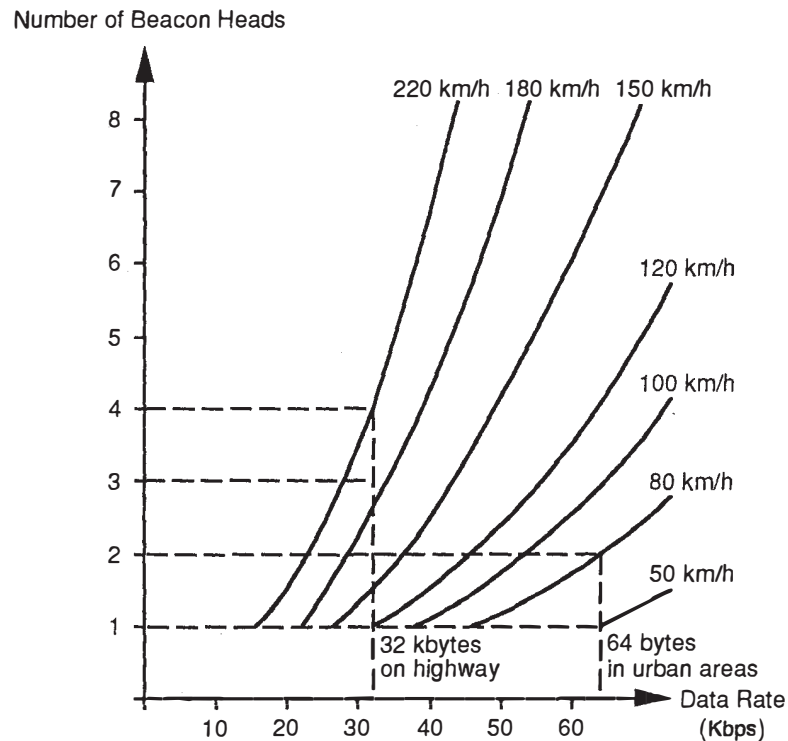


Figure 8.8 Required beacon heads under various transmission data rates and travel speeds.

based on a half-duplex TDMA approach [42]. Each beacon periodically broadcasts a flexible sequence of messages on the downlink and uplink. The downlink contains the Beacon Service Table (BST) and other data, and the uplink contains public and private windows (messages) being transmitted to the vehicle. Under the asynchronous protocol, when a vehicle enters the coverage zone of a beacon, it is able to receive the BST, which contains a list of services offered, along with operational parameters. The vehicle communicates with the beacon by accessing a public window which always follows the BST. Once the vehicle ID has been transmitted to the beacon using the public window, a set of private windows is reserved for further data exchange for this vehicle. If a beacon or vehicle transmission fails, the beacon will retransmit the downlink window and offer an uplink window once the failed window has expired. If no transmission occurs during one of the steps in the sequence, the beacon assumes that the vehicular unit has experienced technical difficulties or has left the coverage zone. The beacon then reverts to its initial state, ready to transmit the BST again.

The synchronous protocol (developed by Hughes) is a fixed-frame structure based on TDMA (Table 8.11). It consists of a reader control message (equivalent to the BST message), activation slots (equivalent to the public windows), and slot data messages (equivalent to the private windows). Detailed information can be found in the draft standard developed by the ASTM to describe a similar protocol [41].

One relatively old technique is also used to provide vehicle-to-roadside communications: the loop detector (or proximity beacon). A loop detector is a magnetic inductive sensor embedded in the road surface to detect traffic volumes and occupancies or to communicate with the vehicle [43]. Loops are typically deployed in a rectangular or circular (for the newer loops) configuration, with one loop per lane. The electronics associated with the loop are generally installed in a control cabinet, together with other intersection control equipment. A recent advance in traffic-flow monitoring enhances the output accuracy of a standard loop detector for counting passing vehicles to only one error in 10,000 [44].

Compared with cellular systems and RDS/RBDS, beacon communications offer high transmission rates, effective position calibration, location-oriented traffic information, and the ability to accurately detect and measure the parameters of vehicles on a specific road or in a specific lane. The disadvantages are that the communication zones are very limited, communication is discontinuous, and system installation and maintenance costs are high.

8.3.8 Satellites

Satellite communications systems consist of a space segment and a ground segment. The space segment consists of the satellite and control station where all the operations associated with monitoring the vital functions of the satellite are performed [45,46]. The ground segment consists of all Earth stations that use the operational satellite. As shown in Figure 8.9, these Earth stations may either transmit or receive.

Satellites can be classified into two broad types: geosynchronous (geostationary or GEO) satellites and low-Earth-orbit (LEO) satellites. GEO satellites orbit approximately 41,326 km (22,300 nautical miles) above the equator. In synchronization with the Earth's rotation, these satellites remain over approximately the same locations on the Earth's surface (near the equator). Because they are far above the earth, relatively large antennas are required. GEO satellites have dominated the field as the technology of choice for many years. Recently LEO satellites have been showing popularity, although most of these systems are still in development. LEO satellites orbit much lower in the sky, typically about 500 to 1500 km (310 to 932 miles) above the ground [with some systems around 10,000 km (6200 miles) above the ground]. Unlike GEO satellites, LEO satellites are not restricted to equatorial orbits. Some of them have circular orbits while others have elliptical orbits. There are little LEO satellites that operate at VHF frequencies (or slightly higher) and carry only data

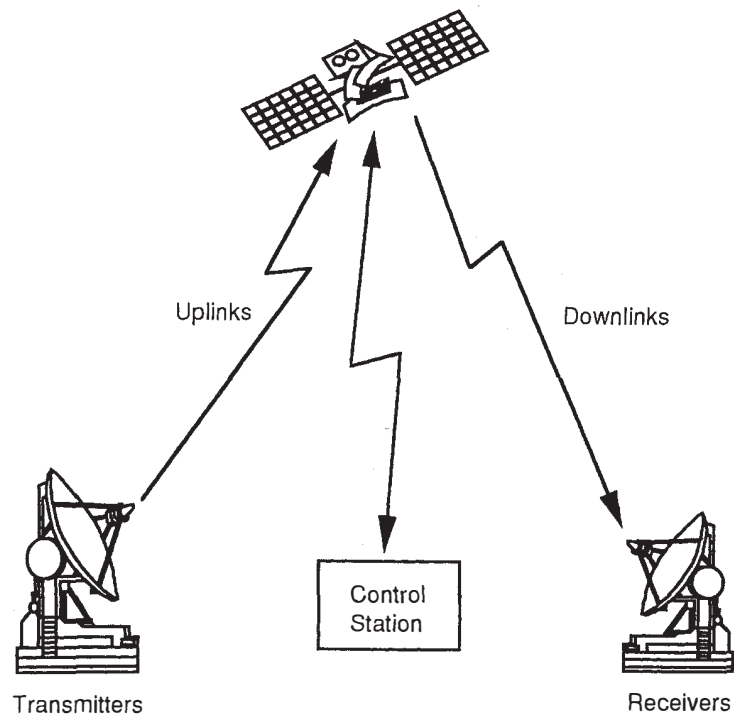


Figure 8.9 A satellite-based communications network.

communications, and big LEO satellites that operate above 1 GHz and carry both voice and data communications (VHF: between 30 and 300 MHz). Each category of satellite has its own advantages and disadvantages.

Despite these differences, all satellites and satellite operations have certain features in common. All communications satellites have transponders. The transponders pointed toward Earth are used to receive signals from Earth stations. They then relay these signals to distant receiving stations on the ground. The former type of transmission is called an *uplink* and the latter is called a *downlink* (Figure 8.8). Some of the early satellites had only one transponder on board, but it is now common for modern satellites to carry a few dozen transponders.

When satellites receive radio signals from ground-based antennas, they cannot simply relay those same signals to a transponder pointing at the ground-based receiving station. Otherwise, this would imply that the two transponders were using the same carrier frequency, which would lead to interference between the uplink and downlink. To avoid the interference problem, the satellite translates the received frequency to a different frequency. It then amplifies the signal for transmission to

the ground, since the signal was weakened during uplink. Although this technique reduces interference between uplink and downlink, additional frequency allocations are required.

Technology has also been developed to control the shape and size of the region on the Earth's surface to which the satellite broadcasts. This area of signal reception is known as the *footprint*, which is a circular or shaped beam from space to the reception points on Earth. Satellite downlinks often have broad footprints for easy reception. To avoid offending certain regions or countries with unwanted signals, a technology for obtaining smaller, better controlled and condensed footprints has been developed. This has enabled the reuse of limited frequencies among satellites for cellular-type networks.

To prevent mutual interference, satellite slots have been established every 2 degrees along the equatorial orbital plane, which means that only 180 slots are available in geosynchronous orbit; few of these slots are still unoccupied. As the number of satellites in orbit has increased, so has the number of transponders aboard each satellite. More frequency bands have been required in order to support this space-based technology. The most common bands for satellite transmissions are VHF, L-band (1-GHz band), C-band (the 3-, 4-, 5-, and 6-GHz bands), and Ku-band (the 11-, 12-, and 14-GHz bands). Table 8.12 lists several existing satellite systems that offer voice, data, and/or position services.

Due to the growing need for mobile communications, new satellite systems will continue to be deployed. Three big LEO systems and three little LEO systems have recently been approved by the FCC in the United States. One big LEO system has also been approved for its frequencies by the World Radio Communications (WRC) Conference. As mentioned in the beginning of this section, the orbits of some systems (Odyssey and OCI) are higher. They are sometimes called medium-Earth-orbit (MEO) satellites or intermediate circular orbit (ICO) satellites. In Europe, one little LEO system, Orbcomm, is already in operation (Table 8.12). The remainder of the planned systems are briefly described in Table 8.13. Readers must bear in mind that the information collected here is believed correct as of this writing. However, it may be changed or updated anytime during the system development phase.

Satellite technology has not been widely accepted for many surface vehicle communications (except the heavy trucking industry) although it has been available since the early 1970s. The main reasons are that the mobile terminals are large and equipment and service costs are high. To attract more users, the size and weight of mobile terminals must be further reduced, and affordable equipment and services must be available while still providing efficient transmission.

8.4 COMMUNICATIONS SUBSYSTEM INTEGRATION

Once the appropriate communications technology has been selected based on the attributes discussed in Section 8.2 and other factors, the equipment must be integrated

Table 8.12
Existing Satellite Systems

Satellite System	Organization	Service	Date of Operation	Coverage	Terminal Types	Voice Coding Rate	Gross Data Rate	Modulation	Channel Access	Voice Bandwidth
INMARSAT-A, B, M, Mini-M (GEO)	INMARSAT	Voice, data, fax	1976, 1993, 1993, 1996	Global, excluding polar regions	Marine vessels, large portables, small portables	N/A, 16, 4.8, 4.8 Kbps	9.6, 9.6, 2.4-4.8, 4.8 Kbps	FM, QPSK, QPSK, QPSK	Voice: FDMA Data: TDMA and TDM	50, 20, 10, 5 kHz
INMARSAT-C (GEO)	INMARSAT	Telex, e-mail, position	1990	Same as above	Land mobile, maritime and aeronautical	N/A	0.6 Kbps (store and forward)	BPSK	TDMA and TDM	N/A
Satellite Paging (GEO)	SpaceCom Systems	Paging	1986	North America	Many types of paging terminals	N/A	1.2-512 Kbps	FSK	FDMA/TDMA	N/A
OmniTRACS (GEO)	Qualcomm	Data, position	1988	Global	Qualcomm terminals	N/A	0.384 Kbps	MSK	SDMA/TDMA/CDMA	N/A
AMSC-1 [Skycell] (GEO)	American Mobile Satellite	Voice, data, position	1995	North America	Mobile data terminals (Mitsubishi, Trimble, Westinghouse, etc.)	4.2 Kbps	6.4 Kbps	QPSK	TDMA	7.5 kHz
Orbcomm (Little LEO)	Orbcomm	Data, GPS data	1995	Global	Land mobile, fleet, cellular data, SMR data, GPS, many applications	N/A	2.4 Kbps uplink; 4.8 Kbps downlink	PSK	FDMA	N/A

Note: N/A = not applicable.

Table 8.13
Planned LEO Satellite Systems

Satellite System	Organization	Service	System Status	Coverage	Subscriber Equipment	Voice Coding Rate	Data Rate	Modulation	Channel Access
Globalstar (Big LEO)	Globalstar, L. P. (Loral, Qualcomm, etc.)	Voice, data, fax, paging, GPS	FCC license Jan. 1995; Commercial operation projected in 1998	Global	Qualcomm design	9.6 Kbps variable	1.2–9.6 Kbps	QPSK	CDMA
Iridium (Big LEO)	Iridium, Inc. (Motorola, Raytheon, etc.)	Voice, data, fax, paging, position	FCC license Jan. 1995; Commercial operation projected in 1998	Global	Motorola, Scientific Atlanta	2.4/4.8 Kbps	2.4 Kbps	QPSK	FDMA/TDMA
Odyssey (Big LEO)	Odyssey Telecom. International, Inc. (TRW, Teleglobe)	Voice, fax, PC data, short messages	FCC license Jan. 1995; Commercial operation projected in 2000	Global	Magellan, Panasonic, Nortel, JPC, Mitsubishi	4.2 Kbps	2.4–9.6 Kbps	QPSK	CDMA
ICO (Big LEO)	ICO Global Communications (U. K.)	Voice, data, fax, paging	WRC approved frequencies Nov. 1995; Commercial operation projected in 2000	Global	Ericsson, Nokia, NEC	4.8 Kbps	7.2–9.6 Kbps	QPSK	TDMA
GE Starsys (Little LEO)	GE Americom, Inc. CLS (France)	Data, position	FCC license Nov. 1995; Commercial operation projected in 1998	North America, Europe initially	TBD	N/A	0.6 Kbps	MSK	DS-SSMA
VITASAT (Little LEO)	VITA	E-mail	FCC license July 1995; Operation projected in late 1997	Global	TBD	N/A	9.6 Kbps	GMSK	FDMA

Note: N/A = not applicable.

with applications at both ends of the wireless network (mobile end and host end). For the most part, each interface is unique to the communications technology selected and will likely be proprietary to the equipment manufacturer. In some cases, however, the equipment interface follows an industry standard and off-the-shelf interfaces may be available. The current trend in equipment interfaces is moving toward the Internet suite of protocols on both the mobile and host ends. This greatly simplifies the task of interfacing new communications equipment at all levels. In addition, an open architecture may be very helpful, especially in terms of allowing users' "plug and play" usage of many different communications devices.

Actual implementation of the network interface protocols may depend on the type of host computing equipment, hardware interface, and operating system or application being used. For example, the host computer may be a mainframe computer, a UNIX workstation, or a personal computer (PC) that might be interfaced to the wireless network via dial-up lines, dedicated phone lines, or other wireline infrastructure. Similar implementation choices must be made on the mobile side. Most implementations on both host and mobile ends conceptually follow the ISO OSI Reference Model as shown in Figure 8.10, except that some layers in the OSI reference model may be added, replaced, or combined in the actual implementation. Each layer in the model provides a specified set of services to the layer immediately above and uses the services provided by the layer immediately below it to transport the message units [47]. The function of each layer is defined as a protocol describing

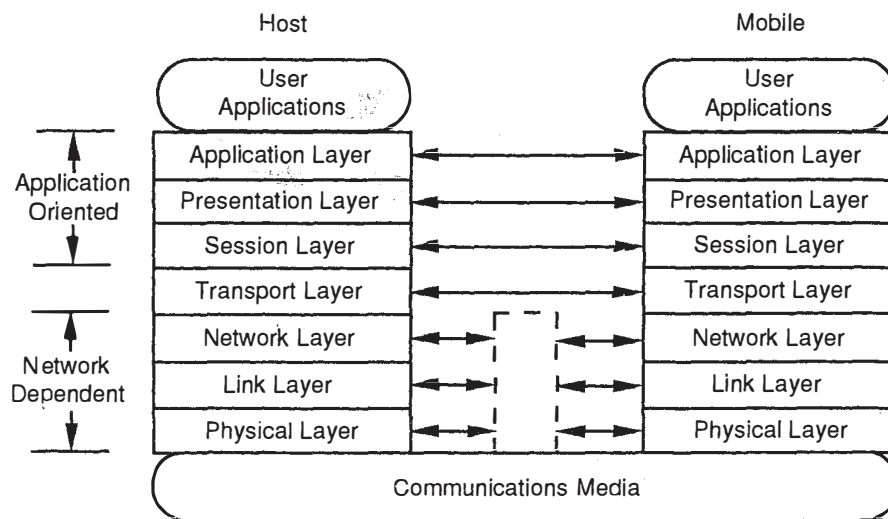


Figure 8.10 ISO OSI Reference Model.

the set of rules and conventions used by that particular layer to communicate with the other layers.

On the system level, the quality of network service must be considered. For data services in particular, the considerations include acceptable error and loss level, average and maximum delay, and average and minimum throughput. For vehicle communications based on existing communications networks, more attention must be given to the transport layer, since the protocol used there can be chosen to optimize use of the underlying network-dependent layers. For integration, it is recommended that a standard set of protocols be used in each of the required layers, although customization will still generally be necessary. For instance, use of the popular TCP/IP (Transmission Control Protocol/Internet Protocol) will make the transport layer much easier to interface with others.

For RF communications, generally speaking, the higher the transmission rate, the higher the BER. Because mobile radios are constantly moving, the operational environment is much more severe than for radios used in a stationary environment. Error detection and correction become an important issue when ensuring reliability of data services. Furthermore, many vehicle location and navigation systems (Chapter 10) are now starting to use existing cellular networks as their communications support. New protocols and standards have become available for cellular data modems. Many different types of modems are now available on the market. However, their performance and ease of use vary. In addition, modem selection is affected by transmission data size and other factors. Therefore, a thorough study should be conducted before committing to one choice.

One possible integration method is to use the stream networking interface standard on either the host or mobile side (when UNIX-derivative operating systems such as pSOS+ or VRTX are used). This standard offers a solution to protocol proliferation problems. Streams were originally developed for UNIX-based network applications. They provide standards for protocol development, interfaces between protocol layers, and interfaces between networks and applications. Streams define a standard set of services for developers to implement protocol stacks that are independent of operating system kernel. This independence ensures portability across different operating environments. Off-the-shelf protocols can be easily integrated into applications containing stream-compatible protocol interfaces. Applications can be written so that they are independent of the underlying protocols and physical communication networks. Because of the popularity of streams, a great deal of off-the-shelf networking protocol software and device-driver software is available for streams. Many existing communication protocols are compatible with streams, which gives users access to a wide variety of networking software. Stream packages for embedded applications in a real-time environment have also been developed. They are much more compact and flexible than the original UNIX version.

The transport layer interface (TLI) is a widely used interface for applications in a stream environment. It can be applied to connection-oriented protocols such

as ATM (asynchronous transfer mode) as well as X.25 and connectionless network protocols such as Ethernet and token ring. TLI can dynamically control or reconfigure stream device drivers, buffers, and timers. It can handle network data in packets or frames.

Similar strategies are available for the DOS and MS-Windows environments. Interfaces for both the mobile and host computer can be written at the DOS device driver level, to support a number of different network standards including the open data-link interface (ODI), packet-driver, and network device interface specification (NDIS), as well as the Virtual device Driver (VxD) and dynamically linked library (DLL) interfaces. Although most interfaces are evolving toward the MS-Windows VxD driver standard, NDIS drivers are portable across environments. One example is that Microsoft Windows NT provides TCP/IP host interfacing via its built-in network components. In this context, serial line internet protocol (SLIP) and point-to-point protocol (PPP) interfaces required by CDPD devices are simple to integrate. Other wireless interface requirements can also be simplified for the application once the underlying communications software has been written to work within the NDIS framework. This task requires a good understanding of the underlying network architecture.

To conclude this chapter, consider all of the communications technologies discussed in this chapter. Some technologies are restricted to one-to-one communications and some are restricted to one-to-many (broadcast) communications. Can you determine one by one which of these technologies are restricted, which technologies can be efficiently configured for one-to-one communication, and which can be configured for one-to-many communication? Furthermore, which technologies are suitable for one-way communication and which are suitable for two-way communications? Similar questions can be raised for many of the other system attributes discussed in this chapter, such as coverage, capacity, and cost. Understanding the main communications capability of each technology should enable us to select the proper network for any particular applications.

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PART II



SYSTEMS

Part II is devoted to a discussion of vehicle location and navigation systems. We shall learn how to use the modules studied in Part I to construct working systems. Vehicle location and navigation systems can be broadly categorized into two classes: autonomous and centralized. Whenever location and navigation functions are performed in the vehicle (mobile end) with no remote host or centralized computing facilities (host end) involved, we will refer to the system as *autonomous*. Otherwise, we will call it *centralized*. This classification is used for the convenience of our study. Different criteria may result in a different classification of systems discussed in this part.

Good system architecture is very important for successful location and navigation systems. Users' requests and developers' improvements generally lead to system expansion. A good architecture must provide a stable basis for the future evolution of the system. In other words, the system must be stable and predictable, but still flexible enough to meet changing demands and operational environments over a reasonable fraction of the expected system lifetime. On the other hand, unrestricted enhancement of a finished system (even when supported by a well-defined architecture to begin with) may affect system stability. Experience indicates that whenever a system is expanded by a factor of two or more, completely new problems will be encountered [1]. Once the architecture has been defined, it is often very expensive and difficult to change it later.

Several of the earlier chapters in this book are devoted to a discussion of the individual subsystems and technological building blocks for intelligent vehicle system architectures. We should always remember that when building a complicated integrated system, many of the architectural building blocks will have their own design specifications or objectives. These objectives may not always be consistent. We must harmonize these conflicting goals in order for the system integration phase to proceed successfully. Furthermore, integration of different modules is not simply a matter of data communication. Many other issues must be considered in addition to the basic system architecture. We will begin looking at these issues with a discussion of autonomous location and navigation systems in Chapter 9, a discussion of centralized location and navigation systems in Chapter 10, and a case study of an operational dynamic navigation system in Chapter 11.

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CHAPTER 9



AUTONOMOUS LOCATION AND NAVIGATION

9.1 INTRODUCTION

Autonomous location and navigation systems can be designed to various levels of complexity. System complexity is generally determined by architectural and design trade-offs. These trade-offs involve various architectural constraints such as system-level requirements for accuracy of location, the unit cost of the system, the complexity of the navigation functions to be supported, whether a wireless communications receiver is required to support the location function, and other considerations specific to the application.

Depending on the user requirements, an autonomous system could be designed to be as simple as a hand-held device or as complicated as a sophisticated in-vehicle navigation system. For example, let us consider the trade-offs associated with developing a low-cost, hand-held, autonomous location device used by recreational hikers or campers. We may assume that market-driven requirements will place a constraint on the cost of materials and production for such a hand-held unit. A simple implementation might be to incorporate a single inexpensive location determination technology, such as GPS, without additional subsystems to correct or remove certain position errors (i.e., DGPS). Thus we have traded lower unit costs for an order of magnitude reduction in position accuracy (most likely 100 versus 15 m) although

some of the inaccuracy is intentionally imposed under selective availability (SA; Section 3.4.2). Additionally, given our cost constraints, we decide that a map display is also too expensive. As a result, the display unit to be used will provide a simple, text-only, black-and-white LED readout of the latitude and longitude of the device. Based on the display selection, we have made another significant trade-off. We have reduced system functionality by not including a map display in the unit. Note that the method of navigation used in this example is assumed to be "manual." Customers may need to plot the displayed latitude and longitude on a paper map (carried with them) to further confirm their location. A system of this minimal complexity may be suitable for recreational purposes such as hiking, cycling, or other low-technology transportation. Other, more sophisticated implementations require more architectural complexity.

A more complicated system implementation might use multiple integrated position determination technologies. An in-vehicle navigation system might use dead reckoning combined with GPS, a sophisticated map-matching capability, and a CD-ROM, hard drive, or memory card-based map database. The user interface may have a heads-up display (HUD) or a touch screen controlled color monitor capable of displaying both text and map graphics in conjunction with speech recognition and speech synthesis capabilities. It might also include route planning and turn-by-turn guidance for trip navigation. Some navigation components could be integrated with existing entertainment equipment already available in the vehicle.

In the remainder of this chapter, we consider both simple and complex implementations for autonomous location and navigation systems. We begin by discussing location determination methods for relatively simple location systems followed by a discussion of the methods used in more complicated navigation systems. Although high-precision location systems can be very complicated (in design and implementation), we use "simple" to indicate that such systems have fewer modules (as defined in this book) than navigation systems.

9.2 VEHICLE LOCATION

In this section, we discuss the location technologies used in mobile applications. A simple location architecture consists of two main modules (building blocks): a locator module and a user interface module as shown in Figure 9.1. As the figures indicates, various technologies are available. Depending on user requirements, we can select one from each module or mix different technologies to construct a working on-board location system.

Even though the architecture of this simple location system seems trivial, the location system is an essential and fundamental component of any advanced location and navigation system. We must pay special attention to the detailed design and implementation issues involved as discussed in Chapter 3. Without a solid location

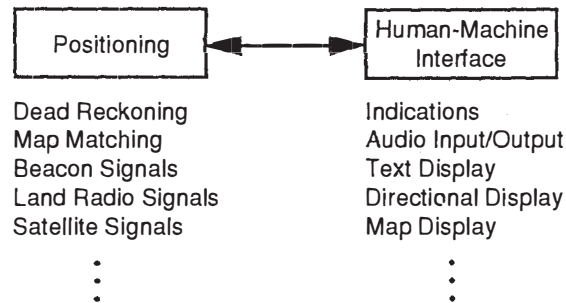


Figure 9.1 Simple in-vehicle location system.

component, any complicated system built on top of it is doomed to have unsatisfactory performance. In the next three sections, we discuss three classes of location technologies that can be employed by a positioning module. For a rough comparison of these technologies, refer to Table 10.1.

9.2.1 Stand-Alone Technologies

The first type of location technology, stand-alone technology, is differentiated from the second and third in that it does not require a communications receiver to determine vehicle location. Recall from Section 3.2 that dead-reckoned positioning, a stand-alone technology, utilizes fusion of sensor data to determine the location of the vehicle. This technology depends on the system deriving an initial vehicle position, receiving a position, or retrieving a position (either entered by the user or stored at the time the vehicle last stopped). It then utilizes distance and directional information provided by on-board sensors to calculate relative coordinates in two-dimensional planar space. Relative distance measurements are usually derived from the vehicle odometer, and directional information is generally provided by a magnetic compass, differential odometer, or gyroscope.

Accuracy may be an issue with systems of this type, due to errors introduced by noise at the sensor, or inaccurate determination of the initial vehicle position. Errors tend to accumulate over time, degrading the long-term position accuracy. Overall, systems requiring a moderate to high degree of location accuracy should not utilize dead-reckoning technology as the sole source for location determination. The advantage of this type of system is that it does not require a communications receiver for position measurement. This tends to reduce the overall cost of implementation. This reduced cost must, of course, be weighed against reduced accuracy. Over the long term, systems requiring more than a minimal level of location accuracy may eventually end up combining this technology with other location technologies.

As discussed in Chapter 4, map-matching algorithms can be used to resolve the inaccuracies caused by the dead-reckoning method. Various fusion technologies mentioned in Section 3.5 are also useful in compensating for the inaccuracy of dead reckoning. There are some alternatives that require external assistance. For example, short-range beacons could be installed on roadside signs or poles to transmit the known positions of these beacons to passing vehicles (Section 8.3.7). These data can then be used to calibrate the on-board positioning system. We will briefly discuss position determination and other applications of these beacons in Sections 10.2.1, 10.3.1, and Chapter 11. You may have already noticed that short-range beacons alone can be used for positioning. The limitation is that short-range beacons cannot locate vehicles traveling in between beacons. If more beacons are installed, this will increase the cost of the system. GPS, LORAN-C, and other technologies can also be used to improve the performance of stand-alone systems. However, once external assistance is being provided, the location technology becomes hybrid rather than stand-alone. These communications-receiver-based technologies are discussed in subsequent sections.

Another stand-alone location technology that does not require a communications receiver for location determination involves the use of a computer vision system. The basic principle of this technology is to store images obtained along the roads before the actual trip and then to match these prerecorded images with a series of images captured by cameras during the trip to identify the location of the vehicle [2]. A similar idea (and some variations on this idea) have also been used in other fields such as robotics [3]. One recent development has involved the integration of computer vision technology and dead reckoning [4]. This system combines the dead-reckoning module with a neural network trained to identify roadway landmarks encoded in a CD-ROM image database, which is correlated with a digital map database. Location determination is performed in real time, assisted by data compression and high-speed video capture techniques. The system is claimed to be accurate within approximately 5m. A block diagram of this system is shown in Figure 9.2.

As a stand-alone technology, this computer-vision-based method has both advantages and disadvantages. On the minus side, the image for the area to be traversed must have been recorded and stored in database form, which means that this technology cannot be used in areas not contained in the database. On the plus side, the system does not require use of a communications receiver for location determination. In addition, the pattern recognition and resultant determination of location is absolute in nature and offsets the detrimental effects of the position errors and sensor errors associated with dead reckoning alone. Although the method discussed uses natural landmarks for positioning, the principle can also be used with artificial landmarks. In other words, specially designed objects or markers could be placed along the road for the sole purpose of position determination, provided the extra installation and maintenance cost is not a concern. This would make the on-board system much simpler. This and other stand-alone technologies might, in a

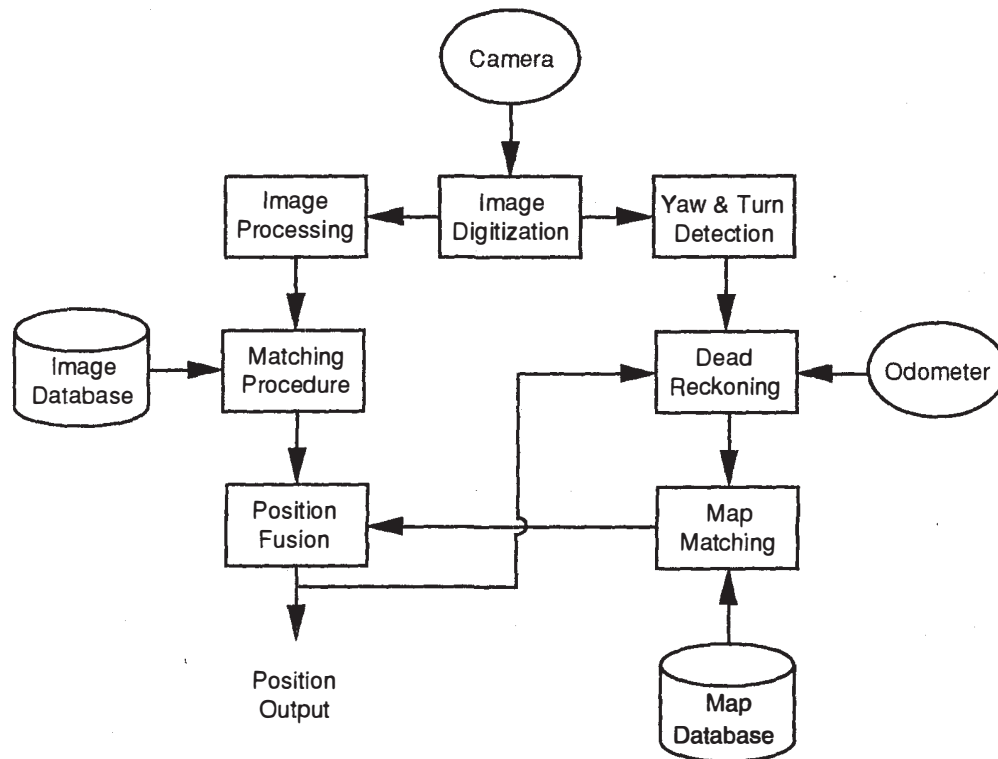


Figure 9.2 A computer-vision-based automatic vehicle location (AVL) technology.

hybrid implementation, compensate well for a common deficiency often found in radio-based location technologies. Many radio location systems are subject to interference (multipath reflection/fading) from large objects such as buildings and hills. By contrast, computer-vision-based technology depends on these same large objects and may provide critical location data precisely where radio location systems lose accuracy. Besides automatic vehicle location, computer vision has been used in other vehicle applications such as automatic driving, automatic vehicle identification, collision avoidance, and automatic incident detection. These systems are beyond the scope of this book.

9.2.2 Terrestrial Radio Technologies

Before introducing actual location systems based on terrestrial radio signals, we first address the techniques commonly used for terrestrial radio-based location determina-

tion. Note that the methods discussed below can be used either at the mobile end or the host end located on a fixed infrastructure. The mobile equipment could be a stand-alone hand-held device. Although most of our discussions are vehicle centered, they can easily be generalized to hand-held devices. Based on the classification described in the beginning of Part II, if these methods determine the vehicle location at the mobile end, the corresponding system is called an autonomous system. If they determine the vehicle location by a host computer on the infrastructure end, it is called a centralized system.

Three commonly used measurement techniques for terrestrial positioning are time of arrival (TOA), angle of arrival (AOA), and time difference of arrival (TDOA). All of these approaches use the concept that the RF signal propagates at a constant velocity and that the signal path is predictable. The first technique, TOA, measures the propagation time of signals broadcast from multiple transmitters at known locations to determine the location of the mobile device or vehicle. This is the same technique used in GPS positioning. The difference is that for terrestrial positioning the emitters are not in space, but on the Earth's surface, typically taking the form of base stations or towers. A detailed discussion of the TOA principle may be found in Section 3.4.2.

The AOA technique uses RF triangulation to calculate the vehicle position. In infrastructure-based implementations, the signal is transmitted from a vehicle equipped with an RF transmitter. In this approach, a phased array of two or more antennas is used at a single cell site to receive the propagating wave. The following equation is often used for the two-antenna array at any one site to calculate the angle of incidence for a two-antenna array located at a single site, as shown in Figure 9.3.

$$\hat{\alpha} = \arcsin \frac{c\Delta t}{d}$$

where $\hat{\alpha}$ is the estimated angle of incidence of the propagating wave (assumed planar) at the antenna array, c is the speed of light (assuming that the radio-wave velocity is approximately equal to the speed of light), Δt is the difference between the times of arrival signal at each antenna, and d is the distance between the antennas used to receive that signal. Note the assumption that the radio-wave velocity is approximately equal to the speed of light, which may not be valid in certain applications.

An interesting special case solution can be made by the observation that a single phase wave striking two closely spaced antennas at any one site will show a difference in electrical phase of the two received signals. Given that $d = 0.5\lambda$ (where λ is a radio signal wavelength), the estimated incidence angle (arriving azimuth angle) becomes

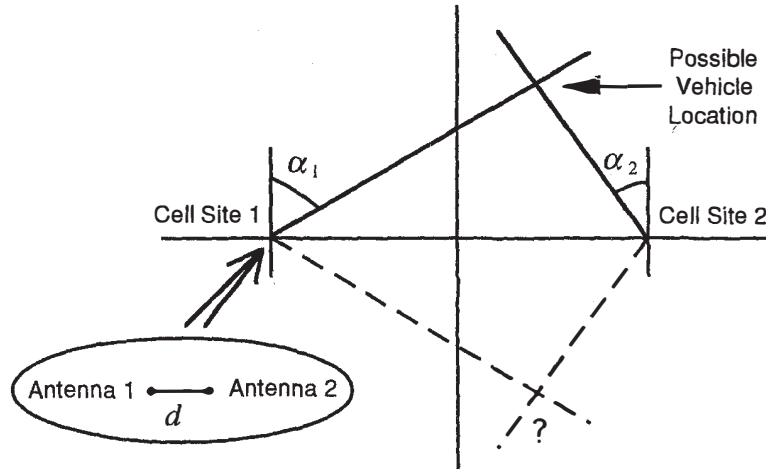


Figure 9.3 Location determination by angle of arrival (AOA).

$$\hat{\alpha} = \arcsin\left(\frac{\Delta\phi}{\pi}\right) = \arcsin\left(\frac{\phi_1 - \phi_2}{\pi}\right)$$

where ϕ_1 and ϕ_2 are arriving electrical phase angles for antennas 1 and 2, respectively.

The phased arrays of the antennas are used at two or more cell sites capable of receiving the propagated signal from the vehicle. The location of the vehicle is determined by the intersection of the two angles of incidence α_1 and α_2 as shown in Figure 9.3.

We have shown an infrastructure-based approach in which each site has two antennas. A three-antenna array is actually better because a two-antenna array will have difficulty calculating the angle of incidence when it is close to a right angle. Theoretically, these antennas could instead be on the mobile side to receive the propagating radio waves from transmitters at the base stations. For economic reasons, antenna arrays are seldom used on the mobile end.

There are both advantages and disadvantages to using the AOA for the determination of vehicle position. On the positive side, there is no need to maintain time synchronization between cell sites (or base stations) to perform vehicle positioning. Only two sites are required to determine the location of a vehicle. Because it does not use a multisite time-synchronized system (as TDOA does), the overall performance of AOA as a location technology should be less affected by RF channel bandwidth. This is an important feature to keep in mind when dealing with various RF technologies [such as 30-kHz AMPS and 10-kHz NAMPS at the low end to 1.25-MHz CDMA at the upper end (Table 8.3)] in a single system.

The major drawback to AOA is its susceptibility to signal blockage and multipath reflection. This results in fairly high error margins for the estimated vehicle positions. This is especially true in urban areas, where errors on the order of hundreds of meters can occur. Because of signal scattering, it is conceivable that position calculations based on AOA could result in a position estimate that places the vehicle in the opposite direction from its actual direction relative to the receiving base sites (as indicated by the question mark in Figure 9.3). These ambiguous solutions can be eliminated using additional technologies such as the RF profile method discussed in Section 10.2.1. Another problem with AOA is that each site or mobile device (depending on infrastructure-based or mobile-based solution) needs to have at least two antennas (which adds additional cost to the system). However, this may not be a problem for some established sites that have a phased array of antennas already.

The third type of a terrestrial-radio-based location technique is TDOA. The TDOA technique utilizes RF trilateration to calculate the vehicle position. RF trilateration differs from triangulation in that it calculates the distance between the vehicle and a fixed set of reference sites that are time synchronized. The calculated distance from the vehicle can be determined by either of two methods, measuring the transit time for a radio signal (group of pulses) between the vehicle and reference sites, or the total phase change in the radio signal between the vehicle and reference sites. The method using pulse modulation for the radio signal is less affected by multipath propagation than the method using phase modulation, which means that pulse modulation is more accurate. On the other hand, pulse modulation requires a higher bandwidth than phase modulation. The radio signal could also be transmitted first from the site to the vehicle with the vehicle then responding back to the site. In this case, the calculated distance must be divided by two. Figure 9.4 illustrates the basic principle of this location technology.

We now discuss how TDOA technology determines a location. If we have a time-synchronized signal (either generated by the moving vehicle or by time-synchronized fixed RF transmitters) at sites 1, 2, and 3 as shown in Figure 9.4, we can determine the signal transmission path lengths d_1 , d_2 , and d_3 . The differences between these path lengths can be measured by the time (or phase) differences of the signals between the transmitters and the vehicle. The estimated location derived from the time or phase difference pairs will be at the intersection of two hyperbolas as shown in Figure 9.4. Assuming that the time difference is used to derive the distance and a receiver in the vehicle is used to receive the signals transmitted from three sites, these hyperbolic curves may be calculated as follows (using the curve h_1 as an example): The mobile receiver detects the pair of transmissions from sites 1 and 2, and determines the difference in arrival times Δt_{12} . This time difference can be translated into a path length difference as follows:

$$d_1 - d_2 = c\Delta t_{12}$$

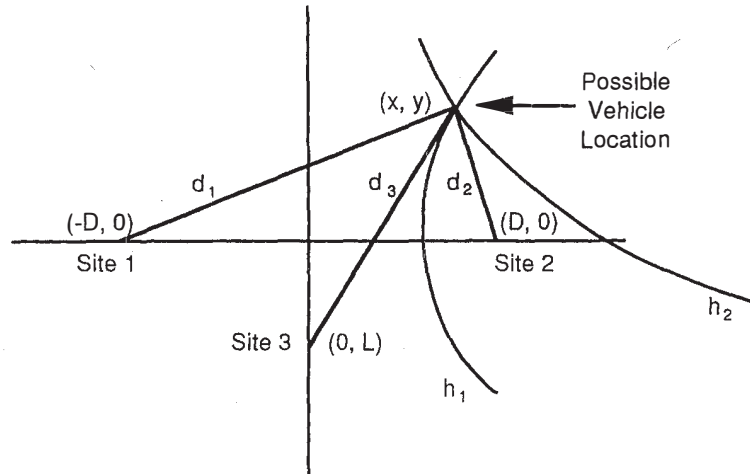


Figure 9.4 Location determination by time distance of arrival (TDOA) or hyperbolic positioning.

As in the discussion of AOA, we assume that the radio-wave velocity is approximately equal to the speed of light (which may not be true in certain applications). Substituting the unknown coordinates of the vehicle and the known coordinates of sites 1 and 2 (as shown in Figure 9.4) into the previous equation, we obtain

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$

where $a = 0.5c\Delta t_{12}$ and $b = 0.5(4D^2 - c^2\Delta t_{12}^2)^{1/2}$. This is a hyperbolic function with the two sites as foci of the hyperbola. (The reader may recall that a hyperbola is a collection of points with a constant difference between the distances to each focus.) Similarly, we can derive another hyperbola h_2 . The intersection of these two hyperbolas is the vehicle location.

Use of the TDOA technique for real-time location calculations requires fewer antennas and is less susceptible to signal blockage, or multipath reflection than using AOA. The main disadvantage of TDOA is the requirement for maintenance of a synchronized time source between all base sites. It may be difficult to implement and maintain the multisite synchronized time keeping accuracy required to measure the propagation of an RF signal. Note that this may not present a problem to the CDMA-based network at all since its sites have already been synchronized. Radio waves have a speed of approximately 300 m/ μ s (984 feet/ μ s), so that a 1- μ s (one millionth of a second) time error in a single site could place a vehicle 300m away from its actual location. Most location systems require a position accuracy of less

than 300m. One technique to solve this time-synchronization problem is to use GPS receivers as discussed in Section 3.4.2.

Another problem with TDOA is that channel bandwidth may impact the performance of this technology. The time difference measurement in TDOA may be affected by the narrow channel bandwidth since high-resolution time measurement requires a narrow pulse (or equivalent), and the narrower the pulse the greater the bandwidth required. By contrast, narrow channel bandwidth is not a problem for the AOA technology. This makes TDOA less accurate in narrowband analog systems than in wideband systems. To improve overall accuracy of location, some implementations have attempted to use a hybrid of the two technologies (TOA/AOA, AOA/TDOA, etc.).

Many terrestrial radio systems can be used to determine location based on the trilateration technology. As we learned, this technique relies on detection of a radio signal from three or more fixed reference points. Some of the better known radio navigation systems are DECCA, Omega, and LORAN-C, but they are much less popular than GPS for vehicle applications. Unlike LORAN-C, the first two systems use phase differences to determine locations.

The DECCA navigation system operates in the 30- to 300-kHz band [5]. It uses a series of three or four transmitters. These transmitters send out low-frequency phase-locked signals that allow a position to be determined from a location of the receiver in the resulting hyperbolic lattice. This position can be translated into a latitude-longitude coordinate or grid reference. The navigation system is mainly used in Europe and run by individual host governments.

Omega is a global navigation system used primarily by maritime and aeronautical users [6]. It operates at very low frequency (10.2 to 13.6 kHz) and was developed initially for use by the U.S. Navy submarine service. Control of the system has since been operationally extended to include a multigovernment partnership. This system has been used with differential techniques for vehicle location purposes in the United Kingdom.

LORAN-C is the "C" configuration of the Long Range Navigation (LORAN) system operated by the U.S. Coast Guard. The "A" configuration of this system was initially used for experiments prior to 1942. The LORAN-C system utilizes three or more land-based transmitting stations whose signals can be used by a receiver to perform hyperbolic position determination. The transmitters use frequencies between 90 and 110 kHz. By 1979, LORAN-C transmitter "triads" had been constructed to cover all North American coastal areas, Northern Europe, the Mediterranean, and the Asian/Pacific coast [7]. Today, LORAN-C provides services to most of the northern hemisphere [6]. For land-based applications, LORAN-C position errors may be as large as 500m. Differential LORAN-C has been developed in an effort to improve position accuracy. Meanwhile, other improvements have been made in LORAN-C during the last few years [8]. The different characteristics and complementary nature of LORAN-C and GPS suggest that it might be useful to integrate them

for vehicle navigation [9]. Further information on DECCA, Omega, and LORAN-C and their applications can be found in [6,10].

On the whole, these terrestrial-radio-based systems are very efficient for maritime and airborne applications. This is partly due to the absence of large obstructions in these environments. On land, however, utilization of these systems results in reduced accuracy because of environmental and man-made obstacles such as mountains and large buildings. These types of obstacles cause signal attenuation and multipath reflection effects, which can limit the effectiveness of a land-based receiver for location determination. For instance, the location errors of LORAN-C and Omega may run as high as 500 and 2,000m, respectively. The ability of a receiving system alone to compensate for these signal distortions is very limited. On the other hand, terrestrial-radio-based systems allow voice and data communications to be merged into one system. Unlike satellite-based systems, some of these systems work inside buildings (as discussed below).

Another interesting form of terrestrial-radio-based location technology has been developed by Pinter [11,12]. This system uses signals from commercial FM radio stations in conjunction with a reference station to calculate the location. This technique uses the pilot tones of FM stations (which are generally in the 19-kHz range) to calculate the location (see Figure 8.6 for the pilot tone signal). The location is determined via triangulation: The mobile receiver converts the phase measurements to the range measurements based on the signals received from at least three radio stations. This technology requires installation of a reference station (observer) at a known location in each metropolitan area; this station plays a role similar to that of the reference station in DGPS. The reference station calculates phase and frequency drift corrections for each FM radio station, these corrections are transmitted to the mobile receiver over an FM subcarrier or other broadcast medium to synchronize the transmissions and stabilize the frequencies. This technology has the advantage of wide coverage due to the high concentration of FM stations in many countries. FM stations can often cover up to $20,711 \text{ km}^2$ (8,000 square miles). Additionally, since FM broadcasts utilize frequencies (87 to 108 MHz) that are lower than GPS or cellular networks, the signal is less affected by obstacles such as buildings or hills. Because the FM signals can penetrate into buildings, this technology can be embedded with many portable device often used indoors. The system has a claimed accuracy of 10 to 20m.

Most terrestrial-radio-based systems generally have a minimum error of at least 150m. The worst systems may have errors of up to 2,000m. As we mentioned earlier, the performance of these systems often deteriorates when approaching urban canyon areas. More studies or hybrid methods (various combinations of the three approaches discussed or with other approaches) are needed to further improve these technologies. For instance, one method to reduce the positioning error would be to implement filtering techniques in the mobile device, which uses the relationship between carrier Doppler phase measurements and range estimate changes. Interested

readers can find information on various other radio location technologies and systems in [13,14]. Many of these technologies have very promising potential for use in vehicle location applications.

9.2.3 Satellite Technologies

Due to the large investment in infrastructure, the number of satellite-based radio location systems is still limited. In this section we briefly discuss two such already used systems. The first system is the global positioning system (GPS). The second system is the EutelTracs operated by Eutelsat. These systems utilize line-of-sight signal reception and the TOA concept to calculate the position of the receiver. Information about other similar systems such as GLONASS and STARFIX can be found in [10,15,16]. Some of them as well as many GEO and LEO systems have been mentioned in Sections 3.4.2 and 8.3.8.

As we saw in Section 3.4.2, GPS is an all-weather, radio-based, satellite navigation system. It allows users to determine three-dimensional position, three-dimensional velocity, and time. The system consists of three segments. The space segment consists of a constellation of 24 satellites. The user segment consists of all the GPS receivers and support equipment. The ground segment is composed of the master control center and many widely separated monitoring stations. Ground control tracks the satellites, determines the orbits, and periodically sends correctional information and other data to the satellites for retransmission to the user segment.

A very simple location system can employ the GPS receiver alone as the position sensor. As discussed in Section 3.4.2, the accuracy of GPS receivers is degraded under selective availability (SA), and much better accuracy can be obtained by utilizing differential correction techniques (at an additional cost). Another approach is to use a dual GPS/GLONASS receiver, which takes advantage of 48 satellites in space (instead of only 24 for a receiver based on GPS satellites alone) and should provide position fixes most of the time, even in urban canyons. Note that GLONASS is not affected by SA. Detailed discussions of the underlying principles and methods for integration with other techniques can be found in Chapters 3 and 4. Note that as of this writing, the U.S. government has decided to conditionally phase out SA in 4 to 10 years, subject to annual review by the U.S. president. This will, of course, improve GPS accuracy for civilian users to a significant extent. However, note that SA may be reinstated at any time (national emergency, war, etc.) and this risk should be considered in the overall system design.

In contrast to GPS, in which the users only receive data (unidirectional transmission), the European satellite location service, EutelTracs, allows for two-way communications. The system uses an on-board terminal to facilitate this bidirectional capability. Vehicles communicate with two satellites, one used for master communications and the other for ranging calculations. The satellites used are in geostationary

orbit 36,000 km above the Earth's surface. The reported accuracy of this system is on the order of several hundred meters [17].

9.2.4 Interface Technologies

The displays used in simple location systems can vary in capability. Design issues to consider are primarily cost, application, and operating environment. Simple text-based LED or LCD displays (as discussed in Chapter 7) are a low-cost means for providing low-bandwidth information to the vehicle operator. These types of displays are suitable for display of positioning information, traffic information, and limited route guidance information.

Other display subsystems that may be incorporated into a simple location application include a graphical map display showing the vehicle's position as a dot on the map. This type of display may or may not allow the user to enter information through a touch screen or other input device. More complicated systems require additional capabilities for user input (see Chapter 7 for additional details on this subject).

9.3 VEHICLE NAVIGATION

Vehicle navigation systems can consist of several integrated system building blocks as shown in Figures 6.1 and 9.5. The five shaded blocks in Figure 9.5 represent devices that can be implemented either as stand-alone components for navigation or as multifunction components that share some duties with entertainment-oriented equipment or other non-navigation equipment. The antennas used by the system can be implemented either separately or integrated into a smart device.

In general, systems created from complicated navigation building blocks tend to stem from requirements that specify features such as greater position accuracy, sophisticated human-machine interfaces, powerful guidance abilities, or integrated radio location receivers. As a result, these complicated navigation systems tend to be more expensive than their simple location counterparts.

9.3.1 Coping With Complex Requirements

In this section, we discuss the system issues associated with the implementation of a complicated navigation system. A typical navigation system may consist of a few or all of the modules depicted in Figure 6.1. Many commercial in-vehicle navigation systems are already available on the world market. These systems are generally implemented using the modules discussed in Part I. Interested readers may find literature on them at ITS-related trade shows and conferences, from magazines, or

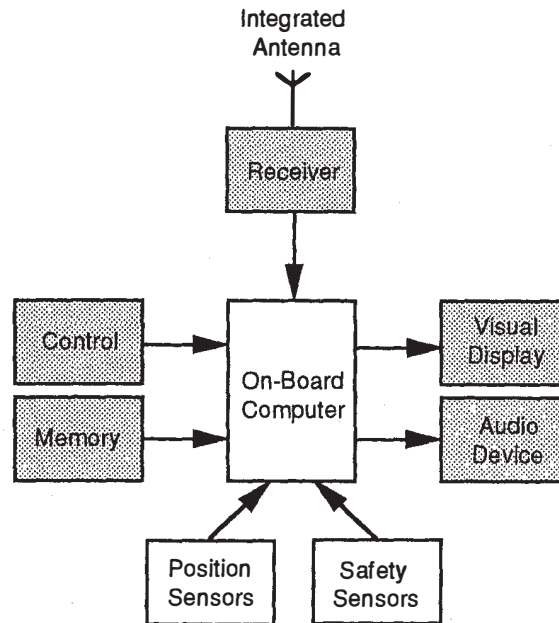


Figure 9.5 Complicated in-vehicle navigation system.

from [18–20]. Because we have already described the basic building modules in detail and will use a complex in-vehicle navigation system constructed from these modules as a case study in Section 11.3, we do not repeat that discussion here, but instead take a look at complicated navigational systems from a slightly different angle.

A thorough understanding of user requirements is a must for selecting and integrating proper navigation modules. The more complex the system requirements, the more complicated the resulting integrated system. For instance, there is a wide variety of choices, even for something as simple as a visual display unit, ranging from a simple black-and-white LED displaying only a few characters to a fancy active-matrix color LCD displaying text and graphics. Our discussion will be illustrated by walking through the system design issues that result from the functional requirements associated with a hypothetical product.

We consider the design of a rental vehicle utilizing an autonomous navigation system. In this design, we assume that the system incorporates a radio location receiver. Because this is an autonomous system, we further assume that the vehicle does not have any integrated wireless communications capability that can be addressed from a centralized facility. Without this communications link, it is obvious

that all vehicle navigation functions must be performed by the system on board the vehicle.

Functional requirements vary from application to application. Some systems might require high position accuracy, whereas others will sacrifice accuracy for unit cost. Increased sophistication in one subsystem can make up for deficiencies in other subsystems. For example, as we saw in Chapter 4, a conventional or fuzzy logic map-matching algorithm can be used to overcome accumulative position errors by determining reasonable best fit locations on a map.

We begin this study by reviewing the following list of high-level functional requirements for the rental vehicle example:

1. The system shall have the capability to determine its current position within 20m of actual location over 90% of its travel time.
2. The system shall have the capability to translate its current position to a map coordinate, and subsequently to a best fit road segment location.
3. The system shall have the capability to display its current position on a map that can be viewed by the vehicle operator.
4. The system shall have the capability to accept a trip destination request and plan a best route to that destination.
5. The system shall have the capability to output audible and visual instructions corresponding to the directional maneuvers required to complete the planned route.
6. The system shall have the capability to determine when it is "off-route," that is, off the planned road segment.
7. The system shall have the capability to correct "off-route" conditions by generating a new route starting at the current erroneous position.

If we look back to our simple hand-held navigation device mentioned in the beginning of this chapter, we can see that it is not capable of satisfying any of these high-level system requirements. At this point we should analyze our requirements and consider their implementation, along with some of the resulting architectural and design issues. Let us begin with the first high-level requirement.

The system shall have the capability to determine its current position within 20m of actual location over 90% of its travel time.

We actually have two constraints on our system architecture as a result of this requirement. The first constraint implies a position solution within 20m of actual vehicle position. This constraint exists so that the system can differentiate between closely spaced road segments. An example of two closely spaced road segments might be an expressway and corresponding frontage road. The 20m resolution is required in order to minimize road-matching errors for closely spaced parallel road

segments. The second constraint extends our first requirement by stipulating that we must be within this 20m limit during 90% of our operating time.

If we assume that a GPS receiver can operate at less than a 20m error (in the absence of SA) it may be possible to meet this 90% requirement. We would have to assume, however, that the satellite signals were not blocked for any more than 10% of our travel time. This is feasible if we are operating in a suburban or rural region without hilly or mountainous terrain. On the other hand, if we spend much of our travel time in an urban environment, it is very likely that we will not meet this requirement. Tall buildings, overpasses, and tunnels will block the GPS signal for significant periods of the travel time, which may in fact amount to more than 10% of operating time. This constraint implies that an additional positioning subsystem will have to be included to offset the deficiencies of GPS in urban environments. Because this additional subsystem should not be susceptible to the same weaknesses as the GPS subsystem, subsystems using similar radio location technologies will not be very useful. This means that a dead-reckoning subsystem is the most likely choice to augment GPS (assuming that a feasible mechanism is available or can be designed for the periodic correction of the dead-reckoning sensors by GPS).

Having two subsystems for positioning will of course increase the complexity of the system. Depending on the sensor fusion method used, some implementations will require arbitration to determine which positioning input takes precedence when the GPS subsystem and dead-reckoning subsystem do not agree. Map-matching methods can also be incorporated into the arbitration scheme to further improve the location accuracy since the next requirement already implies a requirement for a map database. Detailed discussions of sensor fusion and map matching algorithms can be found in Chapters 3 and 4.

The system shall have the capability to translate its current position to a map coordinate, and subsequently to a best fit road segment location.

Because we do not have a wireless communications link to a central facility, this requirement implies that the map database will need to be stored on an in-vehicle mass storage device. The database storage requirements for a reasonably sized metropolitan area (Section 2.6.1) suggest that we may need on the order of 10 to 200 MB of data storage (uncompressed), which includes additional room for possible future expansion of system coverage. Possible choices for storage devices might include CD-ROM drives, magnetic hard drives, or perhaps a PCMCIA memory card. Each of these storage technologies has advantages and disadvantages. The first two have the advantage of large storage capacity. The current capacities for these devices are well above probable storage requirements. Both devices share the significant disadvantage of utilizing moving parts. This disadvantage is due to the extreme operational environment intrinsic to vehicular applications. From extreme temperature ranges to frequent mechanical shocks, the environment is far from ideal for any storage device that utilizes moving mechanical parts, such as CD-ROM drives

or hard disk drives. PCMCIA memory cards do not have this problem because there are no fast moving mechanical parts. However, the reduced storage capacity of the PCMCIA card relative to the other technologies is a disadvantage unless a technique can be developed for rapid compression and decompression. Because of the rapid advance of various mass storage devices, the drawbacks discussed here may not be a problem in few years, but it is still a challenge faced by today's design engineers. In addition to these problems, expensive storage and peripheral devices may very well increase the total system cost, and slow access devices may significantly affect the performance of the various embedded real-time software algorithms.

Assuming that we have selected a storage device, we can now have the system translate the reported position provided by fusion of the readouts from the sensors selected in the first requirement to the format used by the map database. This map database must be navigable, that is, provide information that can be used to plan a route and guide the vehicle. In addition, the map should have a position accuracy of at least 15m, so that it can be used to improve the inaccurate positions provided by the positioning sensors. The augmented GPS positioning subsystem may return vehicle coordinates (latitude and longitude). If the map database selected does not use WGS 84 as its ellipsoid reference as GPS does, we may need to transform the GPS-derived coordinates to the coordinates used by the map database or vice versa. Otherwise, displacements of up to 100m may occur. (Recall that Section 2.3 contains detailed discussions of map reference coordinate systems and transformations between various coordinate systems.) If the vehicle is traveling along a road, the system should be able to use a map-matching algorithm to determine the best-fit road segment. If there is no exact match, the algorithm should be able to find the nearest road segment and snap the vehicle onto it. Otherwise, it could simply use the sensor measurement to determine a position. Additional information on map-matching algorithms can be found in Chapter 4.

Regardless of the storage device selected, this system faces another significant drawback. The database used by this system is static in nature. We need to consider the problem that the database has not been dynamically updated to account for construction, road closures, new road development, and other modifications that might affect the database. This is particularly a problem for drivers of rental vehicles. The driver may be unfamiliar with some local roads, and is relying on the fact that the planned route will not be interrupted or delayed by road closure or construction detours. With a wireless communications capability, this problem can be addressed by incorporating dynamic traffic information. Without a wireless communications capability (as in our case), updates of road networks would have to be accomplished via a less dynamic mechanism, such as periodic map database releases. Even via this mechanism, there is no way for the newly released databases to have current road accident and emergency information. Unless we increase the project budget and add additional components to the system (as we will do in Chapter 10), we must warn the user of the deficiencies in the system. Of course, even the best dynamically

updated database might contain some errors, so error recovery is always an issue in any design. If possible, we should make the system design as modular as possible to facilitate future expansion in later versions of the product.

The system shall have the capability to display its current position on a map that can be viewed by the vehicle operator.

Given this requirement, we can assume that the navigation system will need to include a graphical display, as described in Chapter 7. Again, we need to consider a significant list of human factors issues. Specifically, should the display be backlit? How will the display be affected by glare in daylight? Will it be bright enough to read in the direct sunlight? Where will the display be located? Will it block the driver's vision or cause the driver to divert attention from the road for significant periods of time? Will the display block either the driver's or front seat passenger's airbag safety device? All of these issues must be resolved before installation of a graphical display device.

As we have studied already, many display devices are available. They are based on different technologies and each has its own advantages and disadvantages. Because of the severe operational environment in the vehicle, impressive display units often have high price tags. A tough decision must be made in the trade-off among display quality, user convenience, and the price of the unit because this device may be one of the most expensive components in the whole navigation system.

The system shall have the capability to accept a trip destination request, and plan a best route to that destination.

This requirement is actually a multilevel requirement. The first point we need to consider is the issue of the method used by the operator to input the destination. Is this request done verbally? If not, can we use simulated keyboard entry via a set of switches or a touch screen to enter the street address, business name, or road intersection as a destination? If we allow users to enter addresses as their destinations, we need to make sure that the system can correlate street addresses with digital map coordinates if the database does not contain the coordinates of every possible address. This requires that the map database have attributes of street names and address ranges for each road segment. One method involves matching the desired address along the road using linear interpolation based on the address range for the road segment. The deficiency of this method is that address numbers are not always evenly distributed along a road segment, so very accurate address matching is not feasible.

Once we have settled on a means for inputting the destination information, we need to evaluate the second level in this requirement. This second stage implies that a sophisticated route-planning capability must be implemented. What options do we present the user in terms of how the route should be planned? Some considerations might be given to offering the user a choice among several planning (or route selection) criteria as follows:

- Fastest trip (time);
- Shortest distance (distance);
- Maximize or minimize expressway use (complexity).

Different planning criteria may require different attributes from the digital map database and evaluation functions defined in the algorithm. We also need to decide whether to allow users to select these criteria themselves or to stick with one criterion in the design without giving any flexibility to users. Note that since the system does not have dynamic traffic information, the fastest time choice listed by the system may not be accurate. A detailed discussion of various route planning algorithms can be found in Chapter 5.

The system shall have the capability to output audible and visual instructions corresponding to the directional maneuvers required to complete the planned route.

Like the issues involved in determining how to input the requested destination, we need to consider how the maneuvers associated with a planned route will be presented to the user, as described in Chapters 6 and 7. One issue that is encountered is whether we incorporate an audio subsystem to present instructions to the driver like "turn left at next traffic light," or "exit at ramp 256 east," etc. If so, does the audio subsystem have a volume control so it may be heard over traffic or simultaneous radio entertainment? Visually, how do we tell the vehicle driver to take a "hard" versus a "slight" turn? Such intersections might, for example, consist of both 45- and 135-degree right turns, or of a complicated roundabout.

An additional consideration concerns whether the maneuver is displayed on a separate visual direction screen (turn arrow) or as part of a road segment highlighted on a map (route map). Should the display stick with one consistent format, or use display screens that are sensitive to route guidance context? We may also want to use audible cues such as tones to indicate when to perform the maneuver, etc. All of these considerations will affect the appearance of the device and the acceptance of different user groups, because the display unit will impose the first and probably the most important impression on any user.

The system shall have the capability to determine when it is "off-route," that is, off the planned road segment.

During the route guidance process, we need to determine whether we are actually off-route, or just experiencing an error condition associated with the positioning subsystem. If the position report supplied by the navigation system does not indicate that the vehicle is on a road segment, a heuristic algorithm may be needed to determine whether the position measurement of the vehicle is in error, or the vehicle has left the road purposely to stop at an off-road location, such as a parking lot, driveway, etc., or whether there might be a database error. We expect the system

to automatically detect the problem and perform appropriate action (such as warning or replanning), as suggested in Section 6.3. We may also need to decide whether a manual intervention or resetting mechanism is required to help the system recover from abnormal situations.

Given the static nature of our database, construction detours will probably be interpreted by the system as an off-route condition. A user-configurable mechanism may be needed to allow these off-route conditions to be ignored so that the system does not continuously warn the driver or try to replan a new route when the vehicle is on a detour due to road closures or construction.

Finally, we evaluate the last requirement of the example system.

The system shall have the capability to correct "off-route" conditions by generating a new route starting at the current erroneous position.

Assuming we have encountered a valid off-route condition, the system should recover and replan a new route based on the current position of the vehicle. How should the system warn the driver? Is the replan done in a timely fashion, or does it require an excessive amount of time? What maneuvering directions, if any, should be presented while replanning operation occurs?

We also need to decide how and in what format the system should present the results of a successful replanning operation to the user. In the case study presented in Chapter 11, the system uses the criterion that the new route must be at least 2 min shorter than the original route. Any route that does not satisfy this criterion will not be presented to the user. Other criteria have been used, such as 30% shorter than the estimated trip time for the original route [21]. We may want to conduct several experiments on our own in order to identify the best criterion for this particular project.

As can be seen, this example touched on a fairly large number of design issues. Even though we have not mentioned them, many other issues and low-level trade-offs must also be considered when designing a system of this type. These trade-offs can be inferred from the information contained in the previous chapters. Once we have identified the functions of the system and the proper hardware components to support them, we must take another look at the entire design to make sure that it fits the price range of the expected market and the proposed schedule. Several more iterations are generally required to finally settle on a design that all design team members can agree to. The design team should include key engineers, marketing personnel, and management personnel. Remember, it is generally worth it to spend more time on system specifications and requirements rather than less.

9.3.2 Dual-Use Navigation and Entertainment Components

Vehicle electronics evolved rapidly during the past decade, to the point where they have now been integrated into the vehicle architecture as integral parts of a

sophisticated network. It is natural that many navigation components can be shared with entertainment equipment.

The shaded blocks in Figure 9.5 can support either navigation or entertainment or both. An integrated transceiver might be designed for use with AM/FM radio, GPS, cellular, and paging signals [22]. To reduce cluttered and inconvenient control devices, voice-activated controls, reconfigurable steering wheel controls, and reconfigurable feedback displays can be developed. We know that CD-ROM devices, hard disks, or memory cards can be used for external memory. For instance, a CD-ROM player could be used for storing the digital map database and navigation software as well as for playing music. In addition to serving as a memory device for the navigation system, a memory card reader could also serve other mobile office devices. The display monitor could be used for navigational maps or for commercial TV stations. Similarly, the speaker could be used to listen to turn-by-turn maneuver instructions, ordinary AM/FM broadcasting, or a hands-free cellular phone.

Many available products have combined both navigation and entertainment in a common platform. For instance, the Telepath 100 radio can direct users to a predetermined destination while still supporting all the functions of a normal radio [23]. In this system, the vehicle location is determined using GPS in combination with dead-reckoned positioning and an area map encoded on a PCMCIA memory card. The route is displayed to the driver using directional arrows. AudioNav uses the audio CD player to store navigation data and play music [24]. Many Japanese in-vehicle display units can be used for both digital maps and commercial TV [20].

Before closing this chapter, consider the following question. Recall from Chapter 6, a Braess paradox effect could occur if numerous vehicles equipped with identical navigation units receiving the same dynamic traffic updates were operating on a particular road network. What would happen if the usage of autonomous navigation-equipped vehicles is overwhelming in a popular tourist area? Would the effect be any different if these vehicles all had identical navigation systems or if they had different navigation systems?

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CHAPTER 10



CENTRALIZED LOCATION AND NAVIGATION

10.1 INTRODUCTION

A centralized location and navigation system utilizes some combination, or subset, of the building blocks discussed in Part I. These building blocks can be integrated into both an infrastructure and the vehicle capable of performing dynamic multivehicle location and navigation processing. In this chapter, we attempt to discuss the issues related to various configurations of these systems. From a system-architecture standpoint, three high-level functional blocks are required to perform centralized location and navigation, as shown in Figure 10.1.

The host consists of one or more facilities with the capability to determine the location of or to provide guidance/advisory information to one or more mobile vehicles or devices. For a simplified, simplex (one-way mobile to host) location-determination capability, this component might include a location function, a human-machine module, and an interface to a wireless communication module. In a more complex arrangement, the host may provide full-duplex (two-way between mobile and host) navigational support, complete with traffic data fusion to provide dynamic route guidance based on real-time traffic information. The communications network provides the conduit between the host and the mobile unit. This component has the capability to provide either active or passive support to the location function. As

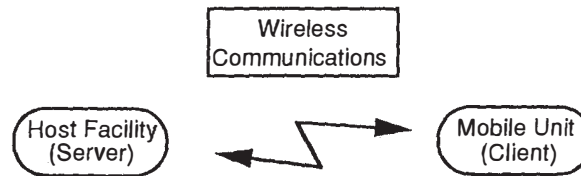


Figure 10.1 Architectural blocks for a centralized location and navigation system.

described in Chapter 8, numerous communications network configurations supporting various throughput levels can be incorporated into this architectural component.

The mobile unit may also function at various levels of location and navigation sophistication. In a simple configuration, the signal radiating from the antenna used by a mobile cellular phone can be used to determine the location of the mobile unit via triangulation data interpreted by a central facility using multiple antennas (as discussed in Section 9.2.2). The operation of this location determination system may be transparent to the mobile handset user. In this simple case, the primary responsibility for determination of mobile unit location rests with the host. In a more complex scenario, the mobile unit will take advantage of one or more positioning capabilities, such as a GPS receiver combined with dead reckoning and map matching. The position derived from the combination of these positioning capabilities is transmitted through the communications network back to the host. The host may then communicate back traffic or dynamic route guidance information directed specifically to the mobile unit.

The applications supported by centralized location and navigation systems are several fold. One important application that can be supported by these systems is a wireless enhanced 911 (E911) location capability. *Wireless E911* is a system with the ability to locate a caller who uses a wireless phone to request emergency assistance (Section 10.4). Ideally, this application would provide the same functionality as land-line-based implementations. Widespread implementation of this capability would probably rely on a location technology that is primarily supported by centralized host facilities and communications infrastructure. The extent of network infrastructure modifications needed to support this capability, weighed against the accuracy of the location determination, becomes an important design trade-off in terms of cost and duration of customer base roll-out. A nonexhaustive list of additional applications for centralized location and navigation technology is provided:

- Emergency private wireless E911;
- Emergency vehicle dispatch and tracking:
 - Police;
 - Fire;
 - Ambulance.

- Public transportation:
 - Bus fleet.
- Private fleet management:
 - Trucking (freight and asset tracking);
 - Taxi services;
 - Trains.
- Secure delivery fleet:
 - Armored vehicles and couriers.
- Private vehicle services:
 - Emergency and roadside assistance;
 - Travel information (route guidance, traffic, weather, gas, food, lodging, etc.);
 - Theft recovery.

The variety of potential applications given in the preceding list for centralized location and navigation systems indicates the need for a diverse set of business and engineering solutions. These solutions tend to have varying economic and infrastructure constraints specific to each particular application. Three main system design issues are associated with these constraints:

- Placement of the location and navigation capabilities;
- Accuracy of locations and frequency of location updates;
- Selection of wireless communications technologies.

The primary issue we need to consider is that of where the place will be for residing the location and navigation capabilities. For example, consider a mobile cellular system manufacturer intending to implement a wireless E911 feature in cooperation with a service provider. This feature is designed to provide the mobile caller's location to the dispatcher (or operator) at an emergency center. The manufacturer may consider a redesign and retrofit the mobile handsets to incorporate the intelligence required for the location determination. The redesign could, for example, involve adding a GPS receiver to the handsets. The cooperating service provider must then consider the time and cost associated with a recall of the existing customer base. On the other hand, the systems manufacturer may decide to retrofit its base cell sites to incorporate TOA, AOA and/or TDOA location technologies as discussed in Section 9.2.2. This places the intelligence of the location determination at the base cell sites, instead of in the handsets. A design using this cell-site retrofit approach may require the addition of "smart" antennas in addition to some level of effort and cost associated with reprogramming the sites. The same considerations hold for navigation, that is, do we design a system with a centralized or distributed navigation ability? In the distributed-approach case, the navigation capability must be resided on the mobile unit.

As far as location accuracy is concerned, we saw in the previous chapters that a wide variety of different location technologies are available. Each has its own accuracy range, and we must select among them based on the system requirements and applications. Table 10.1 lists typical performances for these technologies. This table attempts to give readers a rough idea of the potential of each technology. In actual usage, the performance may depend on a variety of other factors. In fact, many of these technologies will improve over time, and therefore their characteristics will change too. The location technology selected and implemented must satisfy system requirements (as discussed in Section 9.3.1). Similarly, for applications depending on remote location updates, the wireless data update rate needs to be carefully chosen in order to achieve the required system specifications. As we saw in Chapter 8, the specific wireless communications technology selected (and its attributes) has a significant impact on the cost, reliability, and accuracy of the overall system.

In the following sections, we discuss the design and implementation issues associated with centralized location and navigation systems. For convenience of discussion, we first study location technologies and then discuss how navigation technologies can be added to the system. In each category, the centralized approach (placing intelligence on the host) leads the discussion before the distributed approach (placing intelligence on the mobile unit). Despite this distinction, readers should keep in mind the fact that some technologies and systems may not fit into this neat classification. Hybrid approaches or variations of these approaches do exist. All of these approaches and systems contribute to the centralized location and navigation technologies we have today.

10.2 AUTOMATIC VEHICLE LOCATION

An automatic vehicle location (AVL) system tracks the positions of a fleet of vehicles in a particular area and reports the information to a host via a communications

Table 10.1
Performance Comparison of Various Positioning Technologies

<i>Technology</i>	<i>Performance</i>
Dead reckoning (DR)	Poor (poor longer term, but good short term)
Terrestrial radio	Fine (150–2000m, will improve)
GPS	Fair (100–300m with SA and without blockage)
DR + map matching (MM)	Fair (20–50m without loss)
DGPS	Good (10–20m without blockage)
GPS + DR + MM	Better (15–50m continuous)
DGPS + DR + MM	Best (10–15m continuous)

infrastructure. This host can take different forms, such as a dispatch center, a traffic information center, or a transportation management center. All of the technologies introduced in Section 9.2 may be used for AVL. The only addition to the technologies discussed there is that vehicles used in AVL systems must have a wireless communications component (module) to connect with the centralized host facility to which it periodically reports its position. An appropriate infrastructure must also exist to support the wireless communications needs of the system.

Determination of the location of each vehicle typically involves a RF transmission initiated by the mobile vehicle. In one type of system, the sole purpose of this communications system may be to transmit the actual location of the vehicle. In this case, the mobile unit plays an active role in location determination. For example, the transmission may contain a "position report" data packet, which includes the vehicle's latitude and longitude derived using a GPS receiver installed in the vehicle. On the other hand, the mobile unit may play a passive role in location determination. In this type of system, the actual information on the vehicle position may be derived as a by-product of a wireless E911 or a device in the vehicle that can be addressed by an infrastructure. We explore this passive approach to the location determination in the following section, and then consider utilization of the mobile unit as an active participant in location determination in a subsequent section.

10.2.1 Centralized Approach

A centralized location system is a system that uses a host computing facility and communications infrastructure to remotely locate or track a fleet of vehicles within a specific area. In short, the system uses a fixed host facility and infrastructure to determine the vehicle location. The host may take the form of an urban traffic information center or possibly an emergency vehicle dispatch center. Such a system generally includes the building blocks shown in Figure 10.2. Depending on the design, a simple AVL system may not need a sophisticated map-matching module at all. In addition, at least a simple communications component and a simple human-machine interface are required at the mobile end. Note that although our discussions are centered around vehicles, the fleet of vehicles in this system could be a group of hand-held mobile devices.

The host in a centralized location system will generally provide the capability to monitor and possibly dispatch all members of a specific fleet of vehicles. Each of the vehicles in the fleet will have the capability to periodically signal the host via an RF transmission. As a member vehicle of the specified fleet moves within the area monitored and controlled by the host, it periodically transmits or receives a wireless communications signal, which is then processed by the communications network and subsequently delivered to the host facility.

This centralized location capability often requires using the communications network as an active component of the location determination process. For example,

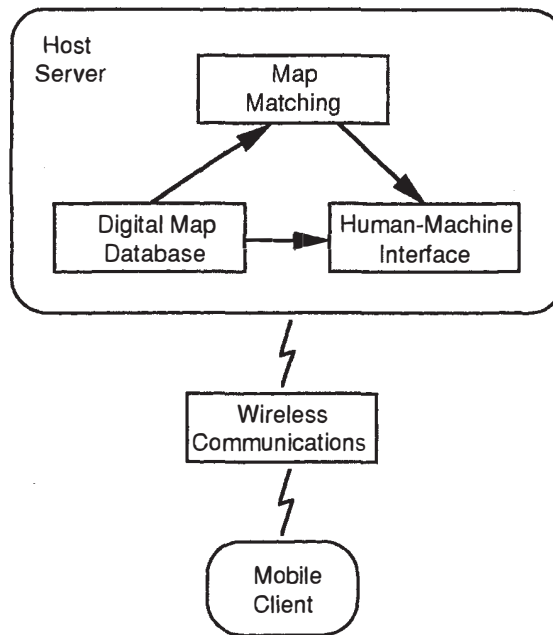


Figure 10.2 Generic centralized AVL system.

since we have a large installed base of vehicles equipped with cellular handsets, and a mandatory requirement to implement location capability in a wireless E911 system (Section 10.4), we should want to avoid retrofitting or replacing all handsets. Instead, we would look for a solution based on performing the location function at each cell site. Currently, three main techniques are used for performing infrastructure-based location determination (as we saw in Section 9.2.2). Recall that the TOA, AOA, and/or TDOA technologies can be implemented on either the host system or the mobile unit. In a centralized location system, all location capabilities are accomplished in the host infrastructure.

Assuming that we have calculated the position of the vehicle within a cellular site, the next step is to allow the host to process the vehicle position data and output the location of the vehicle on a map. For a simple AVL system, it is straightforward to place a dot representing the vehicle position on a map provided the map has been geodetically referenced. Either raster-encoded or vector-encoded maps can be used (Chapter 2). The user must live with the fact that the dot or icon may not be precisely on the road. For more accurate locating, a map-matching module can be used in conjunction with a vector-encoded digital map database. To fully exploit the map database already resident in the host, the system can use the known map information

to filter out the errors associated with the calculated position. The system then translates the calculated vehicle position to map coordinates within the bounds of the monitored area. This translation is achieved via coordinate information available from the map database system.

Given a sophisticated map database system, the data for the reported vehicle position can then be associated with a location on a map display. However, as we discussed, the raw position data still need to be translated into points on the map for viewing. This function could be provided by a modified map-matching module (instead of the in-vehicle map-matching module described in Chapter 4) or other enhanced modules. When defining this mapped location, the errors related to uncertainty in the vehicle position need to be evaluated, and the best available estimate for the location of the vehicle should be derived using a statistical algorithm.

The host will generally utilize an extensive network of high-capacity computing systems. Given this capability, additional dispatching and traffic management capabilities may be incorporated into the host. Besides road segments, shape points, connectivity, road name aliases, street address mapping, and hierarchical level information, the host database can incorporate various other components as follows:

- Vehicle-specific information;
- Vehicle year-make-model;
- Vehicle identification number (VIN);
- Vehicle registration—owner information;
- Vehicle route plans (e.g., fleets for public transportation and delivery services);
- Last reported location (position and direction);
- Last position report time;
- Location-specific information;
- Business names and addresses (possibly including phone numbers and hours of operation);
- Residential names and addresses;
- Points of interest (POIs).

These and other additional attributes could be used by the host to communicate with the mobile unit either verbally (using operators) or automatically (using data channels). Typical services might include providing route guidance instructions and service information to any vehicle in the monitored fleet. This assumes that the mobile and communications components of the system are capable of handling these data services.

A large-scale centralized host has the capability to store or maintain vehicle position and direction information for an entire fleet of vehicles in order to assist in performing the function of plotting vehicles on a display screen. For example, if a series of position reports shows a vehicle to be operating at high speed on an interstate highway, and the latest position reported for the vehicle places it on a

frontage road, the host responsible for tracking the vehicle should be able to validate whether any off-ramps to the frontage road were encountered between the last reported position of the vehicle and its current reported position. If no off-ramps were available, or if the speed limit of the frontage road was significantly lower than that of the interstate highway, the system could assume, with relatively high confidence, that the vehicle's actual position was still on the interstate highway and a position reporting error had occurred. These functions require a navigable digital map database with enough road-related attributes, as defined in Chapter 2.

Other "sanity checks" can also be incorporated into a host to account for system-wide architectural weaknesses. A good example of this would be a host using AOA technology for vehicle positioning. Recall that RF signal blockage and/or multipath reflection may place a vehicle in the opposite direction from the actual vehicle position (Figure 9.3). If this scattering problem is localized to a small geographic area, the map-matching or map database module on the host could use RF profile information to account for and correct this signal path anomaly. The complexity and accuracy of the module and its ability to translate a vehicle's position to a map location is dependent on the resources of the host, the size of the vehicle fleet, the geographic area covered, and the quality of the map itself.

As discussed, each vehicle position report is passed to the map database, map-matching, or human-machine interface module (depending on the system design); the map database information is then used to translate the position into a map coordinate. Once this translation has been accomplished, an icon representing the vehicle and its current location can be output to a host map-display station. The display of all vehicle position information is controlled by an augmented human-machine interface (instead of the in-vehicle human-machine interface module as before). This display can take many forms. For example, vehicles and locations may be displayed as a tabular list of street addresses or as an icon on a road map. A road map may display vehicle information in a form similar to that used by air-traffic-control stations to display aircraft (which combines text with a spatial representation of the aircraft position). The human-machine interface can also take on a wide variety of formats, as discussed in Chapter 7.

The display function of a centralized location system differs from that of an in-vehicle map display. In-vehicle displays are generally only concerned with the location of a single vehicle on a map. The host display function is concerned with displaying information on an entire fleet of vehicles, possibly simultaneously. This function may use various magnification or "zoom" levels to display local and detailed, or wider and less detailed, geographic areas. This allows multiple vehicles to be tracked, but it may be necessary to sacrifice the details of individual neighborhood roads in order to track a large number of vehicles in the area being covered. This zoom capability should be configurable under host operator control, and also automated if necessary in case vehicles move out of the edge of the coverage area. The host should also have the ability to track, in detail, the route of a single vehicle

of interest. This ability is especially important when covering specific emergency vehicles (such as ambulances) responding to an incident.

In addition to TOA, AOA, and TDOA, other technologies can also be used for remote location determination by the host. For instance, short-range beacons or magnetic field loop detector sensors (Section 8.3.7) installed along fixed bus routes and controlled by a host facility may be sufficient to update location information for a public transportation management center. Some literature refers to this technology (and beacon technologies) as signposts and systems constructed from these technologies for automatic vehicle location as proximity AVL systems. Interested readers can find in-depth discussions and analysis of some proximity technologies in [1]. Another available technology is the TIDGET system [2,3]. Unlike traditional GPS-based location systems, the in-vehicle TIDGET receiver does not compute latitude and longitude from the satellite signals. Instead, the on-board receiver passes the raw satellite measurements through the communications network to a host for processing. The host then calculates the location of the mobile, assisted by a map and a reference GPS receiver. Because no location calculations are performed on the mobile unit, the in-vehicle equipment cost is reduced. For a survey of available AVL technologies and applications, refer to [4] and the other references mentioned in Section 9.2.2.

Up to this point we have primarily been concerned with vehicle location from the perspective of the host. The configurations discussed have assumed the intelligence of the location determination would reside in the host and communications network. This approach makes sense when we wish to avoid large-scale or high-cost retrofit/installation of equipment on an existing fleet of vehicles. Next, we will look at vehicle location systems where the intelligence of the location determination function resides on the vehicle itself.

10.2.2 Distributed Approach

A distributed location system is a system that can track the position of a fleet of vehicles within a particular area based on devices at the mobile end that report the information to a host at a central facility. In short, in this system, the individual vehicle or mobile device determines its own location. As before, the central host can take different forms but without the location determination capability. All of the location technologies introduced in Section 9.2 are applicable to this system.

The two most important modules for an AVL system are positioning and communications. As we now know, many different technologies are available for use in these modules. The positioning module could be as simple as a GPS receiver alone or as complex as a multiple-sensor (including DGPS), map-matching-based subsystem [5]. The communications module could be as simple as a one-way data-only link from the mobile unit to the host or as complex as a two-way data and

voice connection. Furthermore, there are various communications media available for wireless connection of an AVL system (as discussed in Chapter 8): simple paging networks, cellular networks, land-mobile radio networks, short-range beacon networks, and satellite networks. The list of different combinations of technologies can go on and on. Figure 10.3 shows one representative class of generic AVL systems, where the human-machine interface could be used for a variety of purposes. One simple example is to display information for the driver. The simplest system could consist of only a positioning module for the mobile client. Note that the host server might have the exact modules shown in Figure 10.2 or just a map database with a human-machine interface.

The system architecture for this generic AVL system is somewhat similar to that described in the previous section, but with the position determination capability hosted on the mobile unit. It is assumed that the host can use the previously described components in addition to providing a server that responds with location information whenever a client vehicle provides position data.

Now we use a very simple AVL system as an example to see how such a system might work. In this system, the only location determination component is an on-board GPS receiver. To reduce the overall system cost, none of the map database and map-matching modules is supported in the vehicle. In this architecture, the

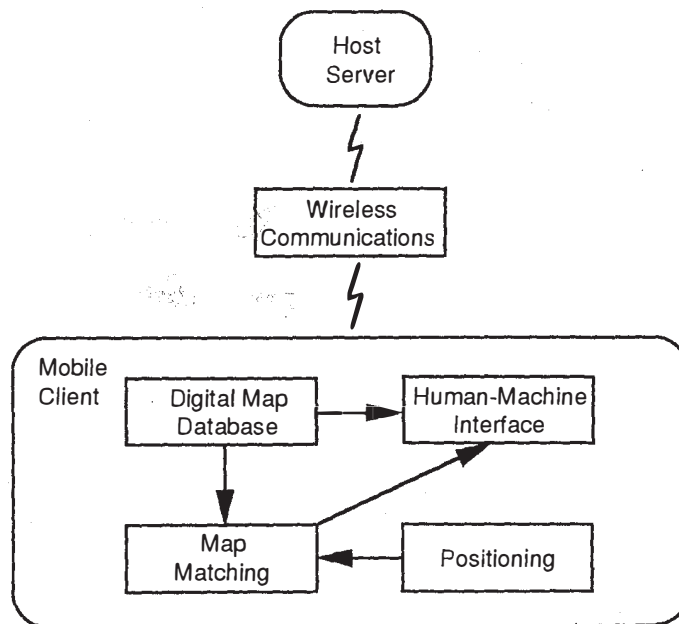


Figure 10.3 A generic distributed AVL system.

mobile utilizes a simple 40-character LCD to display information and dispatch messages. Additionally, the mobile unit will query its position from the GPS receiver every 5 min and report this position to the host while receiving messages from the host. After obtaining the location report, the host will display this location information on its monitor, provided the vehicle in question is monitored. We assume that this system supports a maximum of 100 package delivery vehicles in a single fleet over an RF communications infrastructure.

First, consider the GPS-based positioning. Recall from Section 3.4.2 that the accuracy of the GPS receiver is affected by SA, so that uncorrected GPS measurements are not suitable for applications that require highly accurate position, velocity, and altitude information. However, in our case study we can assume that the package delivery vehicle is following a known route, and the position report it provides to the host only needs to be within a block or two. After receiving the reported position from the mobile GPS unit, the known route plus the position information will provide enough information for the host to obtain a rough estimate of the location (in this application, a rough estimate may be all that is required).

Once the vehicle being tracked has position data available from the GPS receiver, the position is reported to the host. This mechanism is provided by the mobile-based client. This client can be implemented as a software library capable of supporting multiple communications protocols and hardware architectures. The basic logic for this client is to initialize its communications channels and then enter a polling loop that periodically reads the communications channels. Note that we assume that there are two communications devices on board. One is a transceiver for communicating with the host via the wireless communications module and the other is a GPS receiver that provides position information for the on-board positioning module.

The channel initialization algorithm opens the inbound and outbound communications channels for the transceiver separately, implying read-only and write-only capabilities. A third separate initialization procedure is performed on the GPS receiver. The channel to the GPS receiver is read-and-write capable. This allows initialization commands to be sent to the GPS receiver, and responses and position data to be received from the receiver. It is typical for the initialization algorithm to have an automatic error recovery component in an embedded mobile system. This component may use staged recovery logic in an attempt to keep the system operating after a failure has occurred.

Next, we look at the mobile polling algorithm. Once the communications initialization has succeeded, the system will enter a continuous polling loop. A simplified algorithm for this polling activity might look like the following algorithm.

Mobile Polling Algorithm

1. Get the Current_Time.
2. Set the Next_GPS_Position_Query_Time = Current_Time + 5 minutes.

3. Until system termination, do the following:
 - 3a. Get the `Current_Time`.
 - 3b. If the `Current_Time = Next_GPS_Position_Query_Time`, read the `GPS_Position` and set the `Next_GPS_Position_Query_Time = Current_Time + 5 minutes`.
 - Format the `GPS_Position_Message` and send it to the host via the RF outbound channel.
 - 3c. Check the RF inbound channel for an inbound message and its type.
 - If the `Inbound_Message_Type` is an `Information_Message`, format it on the `LCD_Display`.
 - If the `Inbound_Message_Type` is a `Dispatch_Message`, sound a tone and format it on the `LCD_Display`.
 - 3d. Go to step 3a.

In this polling algorithm, we assume that the mobile system has the capability to provide the current time obtained from an on-board source. We could, if necessary, derive it from the GPS receiver itself. However, if we derive the current time from the GPS receiver, our algorithm would have to change so that the GPS receiver is polled each time through the loop to obtain the current time. Regardless of how we obtain the current time, we would only report position data to the host every 5 min, in order to reduce the amount of traffic between the mobile unit and the host. This update rate could be set to some other fixed interval based on the application. At each of the reporting steps in step 3b, the algorithm creates a position message for the host in an agreed-on format, and sends it to the host via the outbound communications channel. At a minimum, this message will contain the vehicle identification, the latitude, and the longitude of the vehicle. The interval timer for controlling of the polling and reporting period is reset whenever the mobile unit receives a position report from the GPS receiver.

Another simplifying assumption made by this algorithm is that the GPS position report can be derived from a single reading every 5 min. To provide a reasonable position report, the GPS receiver must track at least three satellites to obtain a two-dimensional (latitude and longitude) fix. In an urban environment with tall building blockage, this condition may not be met at all times. Several seconds may elapse before the receiver is able to compute a position fix. The receiver may simply output the last known position if it has been on continuously.

Next, the algorithm checks to see if there is an inbound message from the host. This inbound message may be either an information message, a dispatch message, or some other type of message. For instance, information messages might contain information like "On Main St.—5 min behind schedule" or something of that nature. A dispatch message may be preceded by a tone to differentiate the message from an ordinary information message. The algorithm is also simplified in that there is no provision for the driver to acknowledge the receipt of a message, or prevent a new

message from overwriting a potentially unread message. These issues would have to be addressed during system design.

In this case study we assumed that a wireless communications module was available to support messaging between the mobile unit and the host. The communications requirement for this small fleet of delivery vehicles, reporting at 5-min intervals and receiving information and dispatch messages, implies a fairly light-duty infrastructure. For example, the worst-case inbound message rate would be:

$$\begin{aligned} &100 \text{ vehicles} \times 12 \text{ messages per vehicle per hour} \times 30 \text{ characters per message} \\ &= 1 \text{ message/3 sec} \\ &= 10 \text{ characters/sec} \\ &\leq 100 \text{ bps.} \end{aligned}$$

The outbound message rate would be different from the inbound rate, depending on the structure of the information or dispatch messages.

The type of communications infrastructure to be used depends on several additional factors. Some of these factors are coverage, equipment cost, installation cost, maintenance cost, and usage cost. Based on the size of the delivery fleet in the current case study, it is likely that all communications would be run by subscription through a communications service provider. On the other hand, a dedicated network is typically used for controlling a much larger fleets of vehicles or public emergency fleets.

One approach to supporting the communications infrastructure involves using cellular modems. These modems provide data messaging over the cellular network. This tends to be a higher cost method of message delivery in that today's cellular networks are oriented toward voice delivery. For analog circuit-switched data transfer, each inbound and outbound message would require a call to be established, a short message delivered, and, finally, the call disconnected. We could consider leaving the cellular connection up continuously, but this would be expensive and carrier loss due to changing RF conditions (fading) would be likely to occur in this mobile environment. In addition, cellular data modem selections depend on various factors, such as circuit-switched data transfer or packet-switched data transfer, and transmission data rates and protocols. Refer to Section 8.4 for a brief discussion, as well as [6] and the references contained therein for more information on modem selection in cellular-based AVL applications.

Other communications services such as those provided by several private data radio systems or specialized mobile radio (SMR) operators, tend to be oriented toward data delivery. The subscriber equipment costs tend to be significant, but pricing can be set up to be directly related to message throughput, which is low in this case study. An extended two-way paging system may be a reasonable communications solution for this type of application. Messaging rates, subscriber costs, and message delivery costs are a good fit with the communications requirements. In

addition, the communications bandwidth limitation for the host, in this case, may be a function of the number of vehicles in a fleet attempting to transmit simultaneously to the host. We could reduce the communications cost and probably the communications bandwidth by reporting the mobile location back to the host only when necessary. One strategy is to use the communications channel based on the distance traveled rather than the time interval. This will eliminate wasted communications expenses in situations such as the vehicle is standing still and continues reporting its position back to the host.

Another alternative for the communications infrastructure may involve a hybrid combination of technologies. We may be able to use FM subcarrier broadcast for messaging from the host to the vehicles, and provide vehicle to host data through a one-way paging mechanism using packet switching.

The host (server) side of the communications capability would be implemented in a similar fashion to the mobile (client) side. The lower levels of the communications system would most likely queue incoming message reports, which would be processed in a first-in first-out manner. Each received message would be evaluated for vehicle identification and position (latitude and longitude). The received message data might have the following format:

NNN | XXX.XXXXXX | YYY.YYYYYY<CR>

where

NNN	vehicle identifier number (VIN)
XXX.XXXXXX	ASCII-numeric representation of the latitude
YYY.YYYYYY	ASCII-numeric representation of the longitude
<CR>	message delimiter

This message would be time-stamped by the host and passed to the human-machine interface, map database, or map-matching module, which could then use a database to correlate the vehicle ID number with a known vehicle route. This route information, combined with the reported position and delivery time, could be used to assist in accurately determining the vehicle's location along the route. If the latitude and longitude reported are not on the route, the module can then determine the closest route location and map the vehicle to that location. The time-stamp of the received message can also be used as a cue by correlating the vehicle to a known delivery schedule and destination. An outbound message indicating the delivery status of the vehicle can then be sent to the vehicle in response to the reported position message. This outbound message might have the following format:

NNN | T | M[40]<CR>

where

NNN	vehicle identifier number (VIN)
T	message type (information or dispatch)
M[40]	ASCII free form 40 character maximum text message
<CR>	message delimiter

This message would be sent to the mobile unit and displayed on a 40-character LCD. An example message might be as follows: 001 | "I" | "On Main St.—5 min behind schedule." The vehicle driver would only see the text message "On Main St.—5 min behind schedule" on the LCD display. Dispatch messages to the vehicles would take the same message format. It is assumed that we are using an FM subcarrier or packet data service that supports broadcast messages to our vehicle fleet. We could send a message to a single vehicle by using its identifier, an "I" for an informational message or a "D" for a dispatch message such as "Special Pickup at 365 Commercial Ave." A special vehicle identifier such as 000 or 999 could be used to indicate that the message is a broadcast message to be received by all fleet vehicles.

The host/dispatcher station might include a map with the vehicle locations displayed, as discussed in the last section. As discussed in Chapter 2, a preprocessing step may be necessary to translate the vehicle position data format into the format used by the map database. For example, we may need to take WGS 84 position information and translate it to UTM if the map database uses UTM encoding. This translation may or may not be necessary, depending on the system components used. The map database itself can be much more extensive if it resides on the host rather than the vehicle. In addition, the human-machine interface might provide an editing window for the dispatcher to enter vehicle IDs and messages in order to provide informative messages to one or more vehicles in the fleet.

In summary, we have outlined a case study where the intelligence of the location determination is embedded in the mobile unit, which implies a higher cost per mobile unit. We can, of course, increase system accuracy (at added cost) by including additional modules in both the mobile unit and host. For example, in the case studied here, adding more on-board sensors or map-related functions would allow the vehicle to report its position back to the host even when a GPS blockage occurs; this is a very valuable feature for mission-critical applications such as police vehicles [5]. Furthermore, with various modifications, an AVL system could provide location-dependent services, such as mayday, roadside assistance, stolen vehicle recovery, and even route guidance. In the last section, we discuss some applications of these traveler-oriented services.

10.3 DYNAMIC NAVIGATION

A dynamic navigation system uses real-time traffic information to assist users traveling on road networks. In the literature, this technique is also known as dynamic route guidance. The on-board hardware generally includes some or all of the

components shown in Figure 9.5 with the exception that a transceiver is substituted for the receiver. As discussed in Section 6.4, it is much better to use dynamic travel costs than static travel costs for route computation, since the dynamic cost information reflects the actual situation on the roads. These real-time traffic data add one more dimension for the system to solve the route guidance problem, that is, time. In static navigation systems, the cost of each link (or road segment) is fixed. In dynamic navigation systems, the link cost varies with time as road and traffic conditions change. We shall first discuss systems in which the route guidance intelligence resides on the centralized host facility.

10.3.1 Centralized Approach

Centralized dynamic navigation systems rely on a multivehicle (system-wide) route-planning module to guide vehicles on the road based on real-time traffic information. In other words, optimizing each individual route for all the vehicles in a particular road network is solely the responsibility of the host.

Centralized dynamic navigation systems have a central road map database, which can be updated in real time by vehicles on the road acting as probes reporting back traffic information. This database can also be updated using other techniques and methods of analysis. These means include loop detectors, video images, ultrasonic devices, anecdotal information such as police reports and mobile phone user reports, etc. The system includes a centralized multivehicle route-planning module. As we saw in Section 6.4, the main difference between static route planning and dynamic route planning is that the former uses a static database for planning and the latter uses a dynamic database integrated with updated real-time traffic information. The central map database is updated periodically based on the current traffic conditions. The multivehicle route-planning module calculates optimal or near-optimal routes for every possible (or selected) origin-and-destination (O-D) pair or designated-zone pair in the road network. There are essentially two methods: on-demand calculation and periodic calculation. The former is calculated for each driver on request based on the O-D pair submitted by the driver. The latter is calculated periodically for all (or selected) O-D pairs or for designated zone pairs. Detailed discussions of various multivehicle route planning algorithms can be found in the references listed in Chapter 5. Note that multivehicle route planning was briefly introduced in Section 5.1, and a few algorithms were discussed in Section 5.6. After planning, these optimal or near-optimal route data are then transmitted to all vehicles or to designated vehicles at periodic intervals to direct them to their respective destinations. On the mobile side, a destination must be selected by the driver using an in-vehicle navigation device. This information can be used for planning, or (in the case where broadcast route data are being received) it can be used by the on-board system to filter out guidance data irrelevant to its destination.

Figure 10.4 demonstrates generic centralized dynamic navigation. Note that the two-way arrow between the two modules in the mobile unit implies that some implementations may need human assistance or intervention to initialize or reset the vehicle position. Based on the technologies presented in the previous chapters, we know that many variations of this simplified generic architecture are possible. We can add or subtract modules on either the host side or the mobile side to tailor the system in order to meet the user requirements and cost objectives. Because the main emphasis of this book is on the vehicle side of the system, we shall not present a detailed discussion of the centralized approach, but refer interested readers to the references cited in this section for further information.

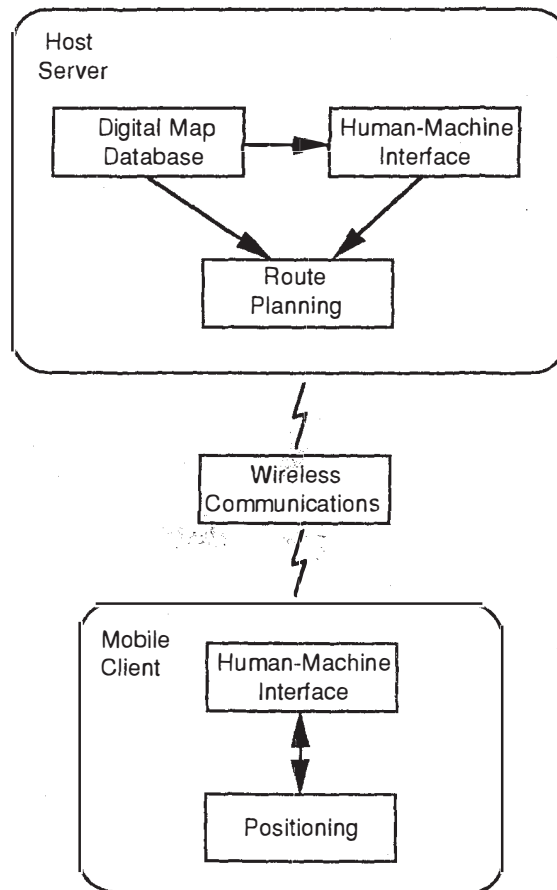


Figure 10.4 Generic centralized dynamic navigation system.

The portion of the centralized dynamic navigation system involving transmission of navigational information can be implemented using the technologies discussed in Chapter 8. One implementation, EURO-SCOUT, uses a short-range infrared beacon network as the communications medium [7]. All maneuvering instructions and relevant guidance icons displayed on the vehicle are derived using data received from roadside infrared beacons, which are connected via cables to a host in a central facility. If a vehicle equipped with a dead-reckoning positioning module deviates from the planned route, the on-board system switches to autonomous guidance mode, and the system displays a directional arrow pointing toward the destination. Upon encountering the next beacon along the road, the vehicle receives new guidance information and once again returns to its normal centrally assisted guidance mode.

In Japan, the concept of centralized dynamic navigation was first investigated in the 1970s [8,9]. This system was tested in the Comprehensive Automobile Traffic Control System (CACs) project. Unlike recent projects in Japan [10], loop detectors (antenna) at the entrances of intersections were used. A more recent field test, the Universal Traffic Management System (UTMS), utilizes a newly developed short-range beacon network as its vehicle-to-roadside communications medium [11,12].

In the following section, we discuss an approach opposite to the centralized one, that is, an approach in which route guidance intelligence is distributed among all vehicles equipped with navigation units. Unlike the distributed approach, the centralized approach can easily avoid the Braess paradox effect (Section 6.4). The overall efficiency and road utilization should be higher for a road network managed by a centralized host. The total cost of constructing a centralized system with simple in-vehicle units is lower than a distributed system with sophisticated in-vehicle units operating under limited centralized control. On the other hand, the distributed approach does not require a very powerful and robust host computer, reduces the heavy wireless communications load, and allows drivers the freedom to select their own routes if the on-board system provides a choice of criteria for route selection. It also places more of the overall system cost on individual beneficiaries.

10.3.2 Distributed Approach

A distributed dynamic navigation system relies on in-vehicle modules for route guidance based on real-time traffic information received from a communications network. In other words, route guidance is solely the responsibility of each individual vehicle.

As in centralized dynamic navigation systems, vehicles equipped with distributed dynamic navigation units receive dynamic information from a host. These systems can also operate as traffic reporting entities (probes) to provide traffic information to the host. Note that other sensors or anecdotal information could be used with or without vehicle probes to provide real-time traffic data. The travel

times required to traverse road segments (or links) are recorded by vehicles or other devices. These travel times are then reported to the host via an RF or infrared wireless communications infrastructure (or some other means of communication). The purpose of these reports is to provide real-time traffic information for each link traversed. Given a large enough sample, the current road conditions (travel times) can be statistically determined; these current road conditions can then be broadcast to in-vehicle units so that they can determine proper guidance activities.

One possible method of displaying the road conditions for operators is to use a host-based map display. It can use the traffic congestion information reported by probe vehicles to show traffic conditions in color-coded format. A route in green may indicate free-flowing traffic, whereas a route in yellow might be somewhat congested. Yellow coding could (for example) be used to indicate delay times greater than one standard deviation in the normal travel time. Red could be used to indicate heavily congested, blocked, or travel times two or more standard deviations above the normal travel time. Vehicle travel speeds can also be used for the same purpose. Figure 10.5 represents the recorded speeds for cars traveling along a link with a speed limit of 55 mph (miles per hour) during a 12-hr period of a day. The horizontal axis represents speed, and the vertical axis represents the number of cars at that speed. This relatively small data sample can be used to illustrate this idea (in actual

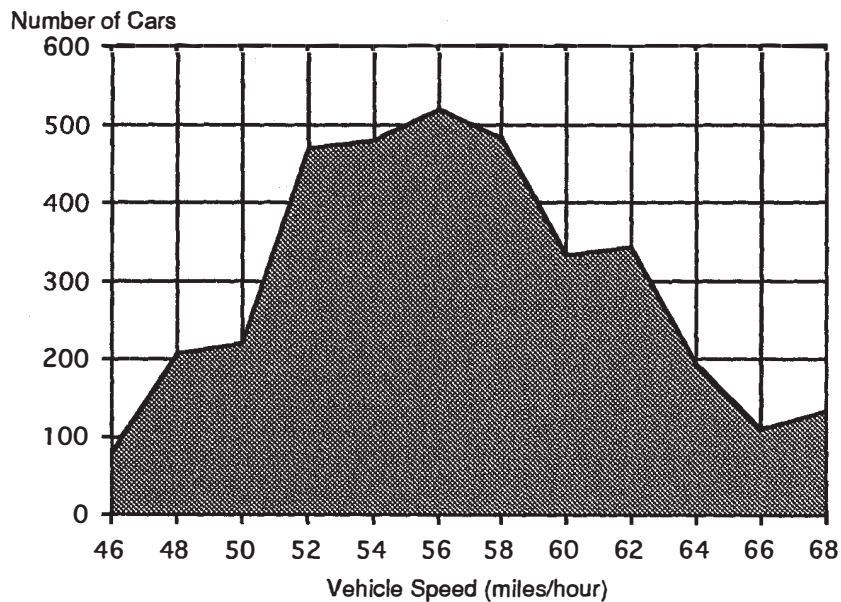


Figure 10.5 Vehicle speed distribution for a 55-mph speed zone on August 24, 1992.

implementation, a longer period of observations is often required to obtain a sufficiently large set of statistically meaningful data). The mean and standard deviation for these data are 56.56 and 4.38 mph, respectively. Using an approximate value of 5 mph for the standard deviation, this link would be color coded green if the current sample of vehicles was traveling at average speeds greater than 52 mph. A yellow color code would be used if the current sample of vehicles was traveling at average speeds from 47 to 52 mph. Average values below 47 mph would be color coded as red. Similar techniques could also be used in mobile map displays or other centralized location and navigation systems.

The average travel times for vehicles may deviate significantly from the normal travel times for a given time period and road segment. The travel times recorded for the 100 block of one major street for the period Saturday 7:00 A.M.-9:00 A.M. may show no congestion at all. By contrast, the same time period on Monday may show traffic congestion. Given this congestion information, properly equipped vehicles may be diverted to a suitable route around the congestion. Traffic management of this type results in higher utilization of the entire road network while reducing overall network travel times. This helps reduce the need for new and existing roadway construction by smoothing out the peaks during periods of increased traffic congestion.

The wireless communications infrastructure for ordinary vehicles has less stringent throughput requirements. Messages can be queued, and queuing delays on the order of seconds are not as catastrophic as they would be in the case of response times for mission-critical emergency vehicles. This implies a less complex and lower cost message delivery mechanism. On the other hand, a reliable, high-speed message delivery mechanism is a must for any system providing emergency services. This principle applies to all the systems we have discussed.

The basic system architecture for a distributed in-vehicle dynamic navigation system is very similar to that shown in Figure 6.1, plus the two-way communications support and the dynamic route guidance components discussed in Section 6.4. In other words, its architecture is similar to Figure 1.3. The host modules are similar to the diagram shown in Figure 10.4, although the multivehicle route-planning module can be omitted depending on the design. Because in the next chapter we will study a working distributed dynamic navigation system in detail, further discussions of the system organization are left to the following chapter.

Many operational field tests of distributed dynamic navigation are currently under way. The System of Cellular Radio for Travel Efficiency and Safety (SOCRATES) projects in Europe plan to use the GSM cellular network as a communications medium to test the dynamic navigation concept [13]. The basic one-to-one cellular links are modified to allow the cell to broadcast to as many SOCRATES vehicles as are in the cell at one time. One of the SOCRATES projects, TANGO, uses the Mobitex packet data network (which is equivalent to the RAM network, Section 8.3.5) to communicate between the host and the mobile unit [14,15]. The

Vehicle Information Communications System (VICS) project in Japan uses infrared beacons, microwave beacons, or FM broadcast subcarriers for the communications channels between mobile unit and host [16]; this system has evolved into an operational system (since April 1996), and in-vehicle units are now being sold to motorists. All of these tests have successfully raised public awareness and interest in vehicle navigation for more efficient, safer, and better transportation systems.

Additional applications, such as requests for roadside assistance, accident reporting, and even on-line ordering of tickets for entertainment events as the vehicle approaches the event location, may also be implemented as part of a dynamic navigational system. Many of these applications could be supported using the architectures described in this chapter.

10.4 APPLICATIONS: MAYDAY

The automatic or semiautomatic mayday (location-dependent emergency call) system can instantly connect vehicle occupants with a service center for attention or assistance, in addition to automatically reporting the vehicle location. Many people view this as a necessary service. In particular, as noted in Chapter 1, most travelers in the United States rate such a system as their top priority when adding new equipment to their vehicles.

In a related vein, we mentioned E911 at the beginning of this chapter. The advantage of E911 over basic (or wireline) 911 is that the public safety official knows the caller's address and phone number. The U.S. FCC has recently made E911 a mandatory requirement for wireless communications services such as cellular telephone, wideband (broadband) PCS, and geographic area SMR (Chapter 8). This additional requirement and upcoming service is called wireless E911. The FCC requires that within 18 months of the date the rules become effective (October 1, 1996), public safety answering point (PSAP) attendants of wireless communications networks must be able to know a 911 caller's phone number for return calls and the location of the base station or cell site receiving the 911 call, so that calls can be routed to an appropriate PSAP; within 5 years, PSAP attendants must be able to locate the caller within a radius of 125m in 67% of all cases (61 FR 40348-40352). These rules could facilitate the development of many vehicle location and navigation applications that use communications infrastructures similar to those used for wireless E911. As we discuss later, current mayday systems integrate GPS receivers with a communication device to automatic report vehicle location. Once the terrestrial-radio-based positioning technologies improve under the FCC requirement, the GPS receiver would yield to them in many location-related applications. It will certainly have a great impact on future mayday systems.

The services provided by a mayday system could be expanded to include many of the following items:

- Emergency services with location;
- Roadside assistance with location;
- Route assistance or guidance;
- Remote door unlocking;
- Theft detection, notification of theft and stolen-vehicle tracking;
- Airbag deployment notification;
- Travel information (traffic, weather, food, gas, lodging, etc.);
- Hands-free and voice-activated mobile phone or pager.

As with the systems discussed above, mayday systems can take many different forms. For a fleet of service vehicles, a mayday system could be similar to the systems discussed in the last two sections. For a private vehicle, a mayday system is usually simpler in system architecture but more human oriented. In this section, we concentrate on this type of system.

One key feature of the mayday system is its human-centered design combined with a cost-effective location capability. An individual mayday system does not need to communicate with the host on a regular basis (as most AVL systems do), so there is no need for a high communications bandwidth. For increased security and reliability, the system should be activated either by the user or by an emergency event detected by one of the safety sensors. Only at this moment is the communications channel established. It then keeps the user in voice contact with a human operator over the communications channel. The system typically needs to have two-way voice and data communications because the vehicle location information is automatically transmitted to the host once the communications channel is established. As we see in Figure 10.6, the system architecture is much simpler.

Because the mayday system includes a service center operated 24 hours a day and 7 days a week, the host facility may be simplified to a map database with human-machine and wireless communications interfaces. The in-vehicle system may be composed of a microcontroller to control a GPS receiver and a wireless communications device such as a cellular transceiver. As an expandable platform, this system could be augmented to include many other services as described at the beginning of this section. This may require some of the other modules discussed in Part I, as well as safety sensors such as an airbag deployment sensor and a crash sensor.

Figure 10.7 shows the on-board equipment of the mayday system, RESCU (Remote Emergency Satellite Cellular Unit), which is available as an original equipment manufacturer (OEM) product for the 1996 Lincoln Continental. The top box in the figure is a cellular phone transceiver. The bottom box contains a microcontroller, a GPS receiver, a modem, and various control circuits. Model year 1997 Cadillacs have just begun to offer a similar system called OnStar in late 1996.

The RESCU system uses a GPS receiver for positioning and an analog cellular phone (AMPS network, Table 8.3) for communications. It can be activated by either of two buttons in the overhead console. The tow-truck button initiates a roadside

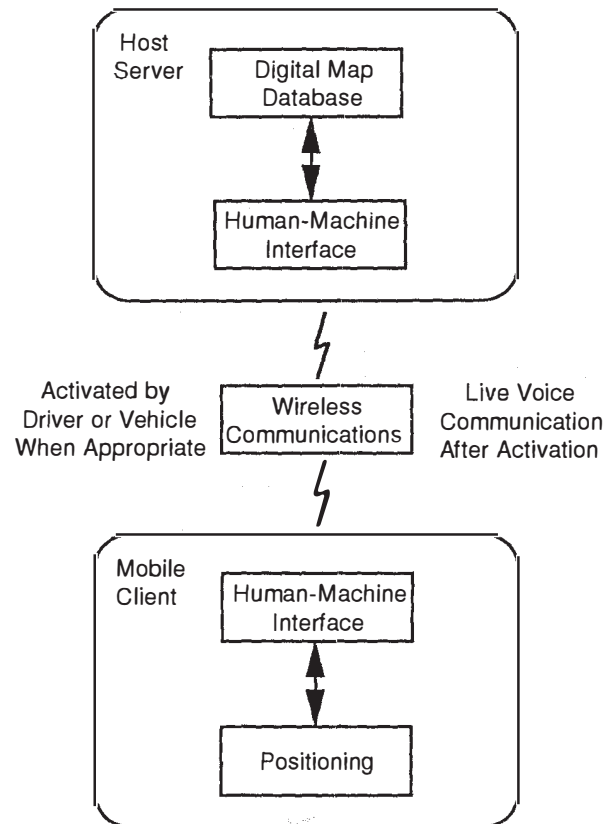


Figure 10.6 Simplified architecture of a mayday system.

assistance call and the ambulance button initiates an emergency call. Once either button is pressed, a warning light located in the overhead console begins to flash. Status messages are then shown on the multifunction display of the instrument cluster. The cellular phone in the vehicle automatically places a call to the service center. Immediately after the communications channel is established, the system sends the vehicle identification number and location information to the host via the voice channel of the cellular phone using a modem. An operator at the center verifies details of the situation via the cellular phone voice channel and confirms the vehicle location using a map provided by a map database module if possible. If required, the operator may maintain direct voice contact with the driver via a three-way call until help arrives and will notify designated family contacts in case of an emergency. If roadside assistance is requested, the center provides an estimated time of arrival and will call back to confirm that the problem has been resolved.



Figure 10.7 In-vehicle hardware components of the RESCU mayday system.

Besides the OEM products offered as options on luxury vehicles, other after-market mayday systems either have been available for some time or will be available. The most notable is AutoLink, which also uses cellular for its communications medium and should be on the market very soon. As proposed, in addition to emergency and roadside assistance, one interesting feature of the system is that the vehicle body computer and engine controller are also connected to the host via the communications link. This makes it possible for the host to open door locks and turn off the engine remotely. To request travel information, drivers must use a phone. For instance, when the driver calls for navigation assistance, turn-by-turn navigation instructions are generated by the host and sent to the driver over the communications network. These instructions will be displayed in text form on the screen of the human-machine interface module. Other alternative methods for displaying instructions, such as instructions produced by a control device or voice announcements, are also possible. These proposed features make AutoLink inexpensive, while still providing basic navigational assistance when needed, in addition to the mayday service. The navigation assistance, route guidance, and other travel information features have also been suggested by others to implement over the cellular telephone network [17]. One appealing point of providing these navigation services over these and other types of communications links is that customers pay for the services only when they need them, and there is no need to update individual map databases as required in autonomous navigation systems.

In addition to these commercial products, there are also several ongoing operational field tests of mayday systems. Interested readers can obtain detailed information on these systems from ITS-related conferences or appropriate Internet WWW home pages [18].

Before studying a practical dynamic navigation system in the next chapter, let us think about one question. Suppose that you are responsible for designing a next-generation location or navigation system. Would you prefer placing the intelligence on the mobile unit or on the host? In other words, do you prefer the centralized approach or the distributed approach?

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CHAPTER 11



A CASE STUDY: ADVANCE

11.1 INTRODUCTION

ADVANCE is an operational test for the Advanced Driver and Vehicle Advisory Navigation ConcEpt project. It was a test of the dynamic route guidance concept in the northwestern suburbs of Chicago, Illinois. To be more specific, the project used a distributed approach, that is, the intelligence of the dynamic navigation system was placed on the mobile unit. The ADVANCE project is a public and private sector partnership. The main participants in ADVANCE include the Federal Highway Administration (FHWA), the Illinois Department of Transportation (IDOT), Motorola, and the Illinois Universities Transportation Research Consortium (Northwestern University and the University of Illinois at Chicago). In this chapter, we learn how various ideas, hardware, and software (or modules) can be combined to form a successful working system through a case study of this project.

The ADVANCE project was launched in July 1991. A major objective was to determine if motorists supplied with real-time guidance could avoid traffic congestion and improve trip quality. The field test was completed in December 1995 with a targeted deployment (see the next paragraph). The project is expected to be completed by the end of 1996. At that time, all documents concerning this project will become available to the public.

Using a combination of technologies including differential GPS (DGPS), dead-reckoning and map-matching-based positioning, RF wireless communications,

dynamic route guidance, CD-ROM map storage, data fusion, and others, the ADVANCE project provided drivers with continuously updated navigation directions and instructions. Although the original project deployment was to have used as many as 5,000 private and test vehicles in a much longer time frame, the recently completed targeted deployment phase had the following features:

- Guidance systems were installed in 80 vehicles.
- Testing was conducted using these existing project test vehicles.
- The "familiar driver" tests using volunteer drivers were conducted for 2 weeks per driver.
- Many aspects of the ADVANCE system were tested in a controlled environment.
- The time frame for testing and evaluation was reduced.

As indicated by the project office, the project gained several benefits under targeted deployment [1]. One of the largest was a financial savings of more than \$27 million due to the reduced test scale and time frame. Additionally, the change in emphasis better supported the transformation of the Traffic Information Center into a regional center distributing travel time information for the Gary-Chicago-Milwaukee corridor. Both of these could be accomplished while still testing many of the concepts within the original scope of the study. Another important benefit of the targeted deployment was a quicker turnaround on reports back to the industry, because the overall time frame had been reduced. On the other hand, targeted deployment will have an adverse impact on the statistical significance of some of the data collected and evaluations conducted. We address these issues in the last section of the chapter.

The entire ADVANCE test area covered more than 776.66 km² (300 square miles), including portions of the City of Chicago and more than 40 communities northwest of Chicago (Figure 11.1). The project included the high-growth areas adjacent to O'Hare International Airport, many offices and retail complexes, road development corridors, and major sports and entertainment complexes. The population in the area is more than 750,000.

The main components of the ADVANCE system were the traffic information center (host) and in-vehicle navigation system (mobile unit) wirelessly connected by a RF communications network. In the following three sections, we discuss each of these components in detail. The chapter concludes with a final section describing the initial evaluation results of the project.

11.2 TRAFFIC INFORMATION CENTER

The ADVANCE system consisted of four subsystems: the mobile navigation assistant (MNA), RF communications network (COM), traffic information center (TIC), and

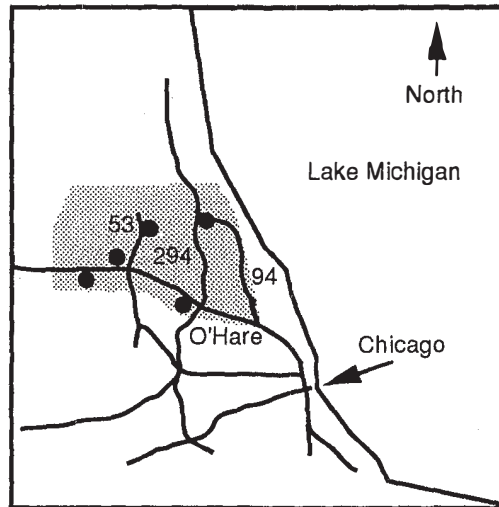


Figure 11.1 ADVANCE test area.

traffic-related functions (TRF) [2]. These subsystems are shown in Figure 11.2. Because the TRF is closely associated with the TIC, we discuss them together in this section. The MNA and COM are discussed in Sections 11.3 and 11.4, respectively.

The TRF was physically located in the central computer facilities of the TIC and provided transportation-related data and analysis functions using various software processes. A process or task is an abstraction of a running program. In other words, the TRF was a software package that generated both static and dynamic (real-time) traffic information. The static traffic information was developed off-line and was stored in the form of off-line historical profiles. These static profiles were later used by the MNA database compiler to generate route-planning attributes as discussed in Section 6.4. The dynamic traffic information was broadcast to the vehicles on-line in the test area periodically during each predetermined cycle.

To generate the initial static profiles, a large and detailed traffic (equilibrium) flow model was developed [3]. The inputs to this model were the ADVANCE network representation and origin-and-destination (O-D) flow matrices. The static profiles produced by this model were essentially the estimates of initial link travel times, where each link represents a segment with turning delay information.

The ADVANCE network representation was an integrated database for the test area. This database combined elements derived from three sets of data. These data were the NavTech database (Section 2.5.2), the north-northwest network of the Chicago Area Transportation Study (the transportation planning agency for the Chicago area), and traffic signal turning data collected in the field by the staff of

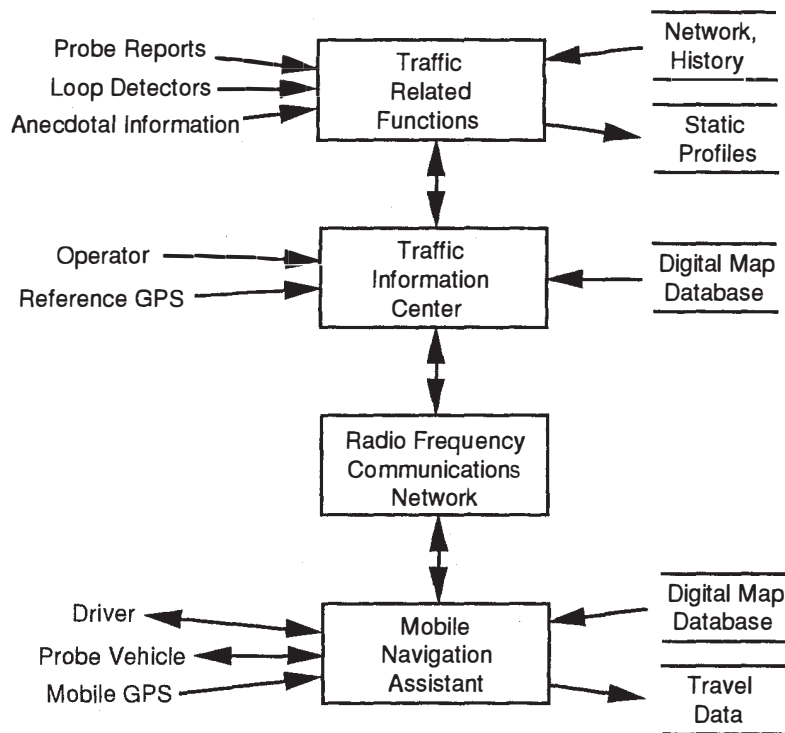


Figure 11.2 ADVANCE subsystems.

the Urban Transportation Center associated with the University of Illinois at Chicago. Based on these data, all arterial and collector streets were identified, mapped, and coded with respect to street and highway segment attributes. All together, the network representation for the test area consisted of 7,253 directional links. These links intersected in 1,580 intersections. Of these intersections, 699 had signal lights. Note, however, that the map database in the vehicles was significantly larger than the test area. Signals along arterial and collector streets were represented using the link delay functions to be discussed shortly. The test area was defined using 274 boundary links. To represent turning movements, each link included the relevant turning movement. For example, before adding turning movements, one segment was sufficient to represent a road segment approaching a four-way intersection. Once a turning movement is added, it must be divided into a left link, a straight-through link, and a right link. As a result, the total number of links in the network increased by a factor of approximately 2.5.

The O-D flow matrices were tables describing the flow (in units of vehicles per hour) from each possible origin to each possible destination. The origins and

destinations were defined in terms of small zones. These zones were about 0.65 to 10.36 km² (0.25 to 4.0 square miles) in size. All zones were inside the test area. These tables were obtained from the Chicago Area Transportation Study performed in 1990. They were part of the input to the traffic flow (network) model described next.

A traffic flow model was developed in order to obtain initial estimates of link travel times (including turning movements) for various time periods during a 24-hr weekday. The five time periods for a normal weekday are listed in Table 11.1. These estimates (static profiles) were used as initial values for the dynamic route guidance system. The model was a generalized version of the traditional traffic assignment model [4].

Two new features were added to this generalized model. First, a delay function was defined for each turning movement link based on the Australian method [5]. The standard model depends only on the flow along the particular link in question. By contrast, these delay functions determined the appropriate traffic signal control parameters for each intersection in relation to the link flows in the solution. The link delay in this model becomes a function of the flows on conflicting links at the intersection. At intersections without signal lights, the delays are functions of the conflicting flows. In other words, this function incorporates many factors such as number of lanes, left turn pockets, number of phases in the traffic signal, and speed limits. It provides estimates of the average delay per vehicle as a function of the link flow to capacity ratio. Second, the model was solved for the 5 weekday time periods listed in Table 11.1. These five solutions were not correlated. After initial field testing and data collection, these profiles were updated regularly off-line during deployment with actual travel times collected using probe vehicles and other traffic data. Probe vehicles are vehicles that report real-time traffic data for the roads on which they are traveling. The static-profile updates were based on weighted averages of probe data, detector data, and other information discussed later.

We now describe the process used to produce the dynamic traffic information (which was different from the processes described earlier for generating the static profiles) [6]. This process analyzed all incoming data and made incident reports and

Table 11.1
Time Period for Normal Weekdays

<i>Period</i>	<i>Time</i>
Morning peak	6 A.M. to 9 A.M.
Midday	9 A.M. to 4 P.M.
Afternoon peak	4 P.M. to 6 P.M.
Evening	6 P.M. to 12 A.M.
Night	12 A.M. to 6 A.M.

predictions about future travel times. The output of these reports was broadcast to vehicles within range of the RF signal of the COM subsystem (module). Vehicles outside the test area approaching or crossing the test area were able to receive dynamic link updates and plan dynamic routes using static information from outside the test area and dynamic information inside the test area. The dynamic traffic data were developed using three tasks of the process: incident detection, data fusion, and travel time prediction (Figure 11.3). These three tasks were executed once per 5-min interval.

The incident detection task provided reports for nonrecurrent congestion. This task consisted of three algorithms. The probe algorithm compared the reported travel time to historical travel time and used the ratio of the two travel times to determine if an incident had occurred. The loop detector algorithm also compared the current traffic volumes and occupancies to historical data to determine if an incident had occurred. (As discussed in Section 8.3.7, loop detectors are magnetic inductive sensors embedded underneath the road pavement to detect the traffic volumes and occupancies.) For detailed discussion of the incident detection based on data provided by loop detectors and probe vehicles, refer to [7]. The raw loop detector data received could be viewed by the operator in a log file window. These data were received from two sources. One was from the Illinois Department of Transportation Traffic Systems Center at 1-min intervals. The other was from the Dundee Road closed-loop signal system at 5-min intervals. The anecdotal information algorithm parsed data received from other facilities. These data included police/fire reports obtained from Northwest Central Dispatch; weather data provided by Surface Systems, Inc.; lane closure data provided by the Illinois State Toll Highway Authority and IDOT; and user reports from *999, which is a cellular-phone-based motorist call-in system. By fusing these data and combining them with the probe and loop detector reports, the fusion task described next decides whether an incident report needs to be issued. Incidents could also be entered manually into the system.

The data fusion task performed three functions in addition to generating incident reports. First, it screened the input data to see if they were consistent and reasonable. For instance, if the probe data were good, they were compared against the loop detector data to see if these loop detector data showed similar results. Second, it converted the loop detector data into travel times by estimating the travel time from the volume and occupancy data. Finally, it estimated the current travel time (fused travel time). If the loop detector was not reliable or malfunctioned, the current travel time was the average of the probe travel times. When both sets of data were available, the following equation was used to estimate the travel time for each road segment:

$$t = \frac{k_p \frac{N_p}{\delta_p^2} t_p + k_d \frac{w_d}{\delta_p^2} t_d}{k_p \frac{N_p}{\delta_p^2} + k_d \frac{w_d}{\delta_p^2}}$$

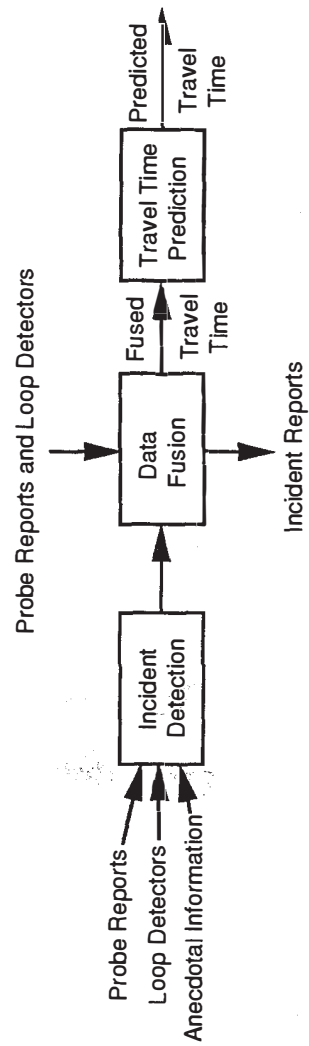


Figure 11.3 Real-time data flow in TRF.

where the subscripts p and d indicate the probe and detector data, respectively; k represents the fusion adjustment factor to control the contribution of each piece of data; δ represents the standard deviation in the corresponding travel time; N_p is the sum of weights for reasonable probe reports; t_p is the mean travel time reported by the probe; w_d represents the weight assigned to the loop-detector travel time; and t_d is the travel time converted from the loop-detector data.

The travel time prediction task used all of the outputs generated using the preceding algorithms to compute travel times for the next four 5-min intervals (these algorithms were executed every 5 min) for 20 min. If an incident occurred, the actual or expected duration of the incident was used as the predicted travel time. Otherwise, the travel times were predicted on the basis of fusion data. Three steps were used. First, the data were aggregated into a single value for the interval. Second, the data were standardized using the mean and standard deviation of the travel time for that link. Finally, the travel times were computed based on the standardized data, link parameters, and other time-related parameters. The final results were in a form ready for conversion to link travel time update messages.

The TIC provided all of the centralized computing resources for ADVANCE. For readers who have not had the opportunity to see a real navigation system and the associated hardware, we will list the sizes of some of the equipment used in this system (Figure 11.4). The hardware components of the TIC were housed in a 178- × 48.4- × 76.2-cm (70- × 19- × 30-in.) standard rack cabinet [6]. The central computer was a SunSPARC 670MP (multiple processors) server with four 70-MHz super-SPARC processors. It had several dual-wide versa module Eurocard (VME) bus slots for expansion. This server had 128 MB of dynamic RAM, 13.6 GB of ROM, a 5.0-GB off-line storage tape drive, and one CD-ROM drive. The server had two 16-port synchronous interface cards that were used for external communications. Additional equipment housed in the cabinet included a modem rack with 16 slots containing 14,400-baud modems. Other stand-alone modems were also used to accommodate modem incompatibilities for leased telephone lines. The main operator consoles were SunSPARC X-Terminals interfaced with the server via 10-BaseT Ethernet. The ac power was supplied through an uninterruptible power system whose internal batteries could provide a 2-hr supply in case of a power outage.

All of the software modules in the TIC interacted with the TIC database and each other using the *interprocess communication* protocol. The interprocess communication protocol is a well-structured non-interrupt-driven communications protocol for software processes [8]. In addition to the TRF processes already discussed, the other software processes or modules supported the user interface and system communications. Like the vehicle databases discussed in previous chapters, the TIC database also contained both static and dynamic data. In addition to the digital map database derived from the NavTech database, it contained static profiles, loop detector reports, probe reports, etc.

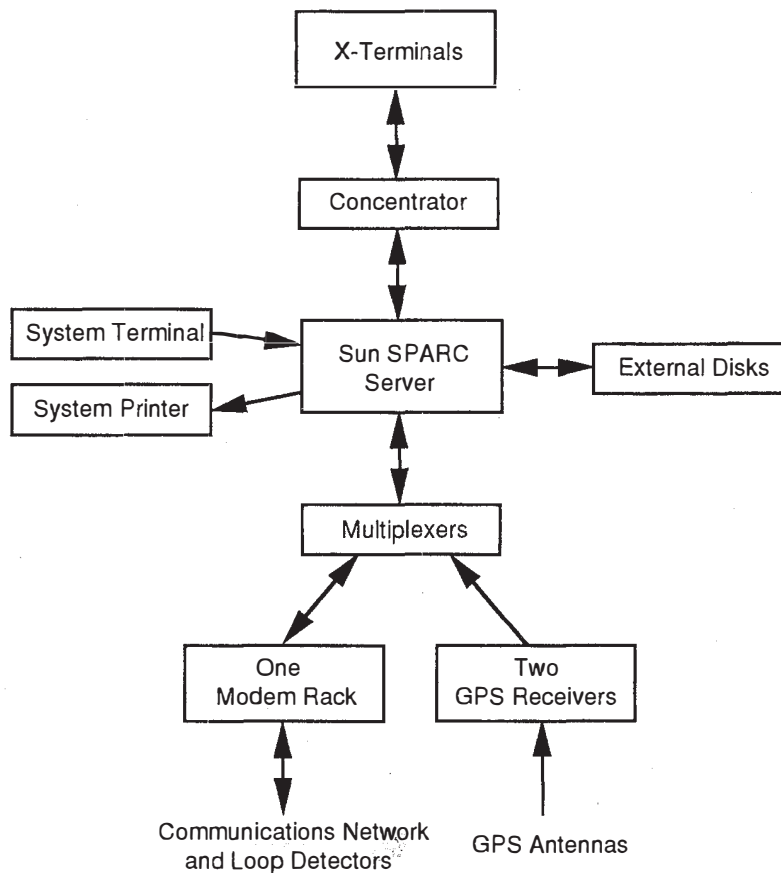


Figure 11.4 TIC hardware configuration.

The TIC user interface allowed the operator to interact with and control other modules. It could start or stop the entire system, turn various TIC subsystems on or off, monitor the current state of the road network, maintain user account information, and be used to input anecdotal information such as police reports and mobile phone user reports. The display window for monitoring the road network could be used to show the map in different ways via pull-down menus, vertical and horizontal scroll bars, and a mouse. It could be used to select one or more road segments and retrieve information such as street names, city names, zip codes, addresses, travel-time profiles, probe reports, loop detector data, and traffic incidents.

All communications-related tasks were handled by inbound and outbound message processes. The inbound process managed the reception and storage of

reports from probe vehicles. Each probe report message was validated on the basis of a unique identifier code. The outbound message transmission via the COM module was handled by the outbound process, a scheduler within the communication module. Each outbound link update message contained a link identifier (ID) and link update information (updated travel time predictions). All the outbound messages were kept in a list in the scheduler which decided when to broadcast these messages. As configured for the targeted deployment, the scheduler allowed for a 4-sec gap between outbound messages to ensure that the COM subsystem did not become overloaded. GPS correction messages [containing DGPS correction data (Section 3.4.2)] were broadcast at 16-sec intervals. Updates of link travel times were transmitted as frequently as the volume of updates permits.

11.3 MOBILE NAVIGATION ASSISTANT

The MNA subsystem determined the position of the vehicle using dead-reckoning sensors and DGPS, with assistance from a map-matching algorithm. This module performed route planning based on current traffic information received via the COM subsystem and also provided route guidance instruction to the driver in the forms of both visual display and voice output. Meanwhile, as mentioned, MNA also provided real-time travel time reports for transmission to the TIC. The high-level architecture of this module is identical to that in Figure 1.3. To help visualize the locations of the various system hardware components, Figure 11.5 shows the

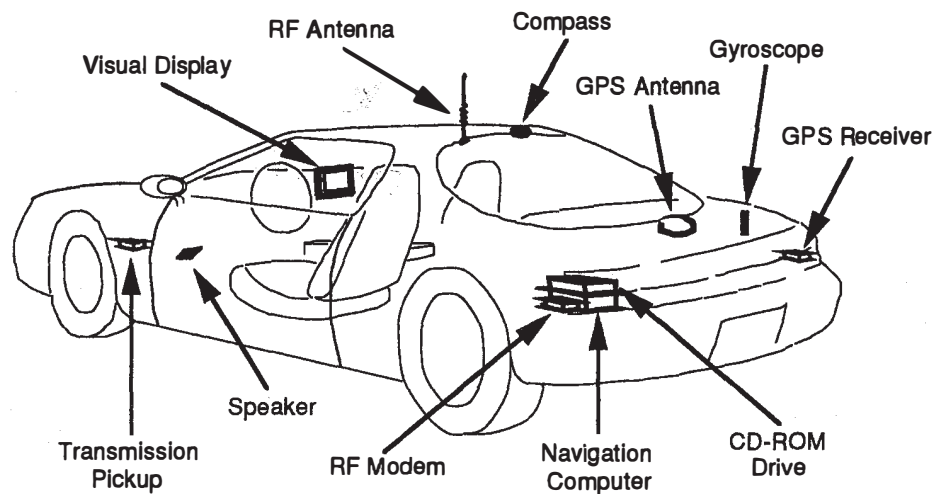


Figure 11.5 In-vehicle equipment for ADVANCE.

in-vehicle equipment used by the MNA. The connecting cables and wires have been omitted for clarity. Figure 11.6 shows the actual in-vehicle MNA display unit.

11.3.1 Hardware

The MNA hardware configuration is shown in Figure 11.7. The speaker and display unit with their controller were installed adjacent to the driver as shown in Figure 11.5. A PCMCIA memory card was provided in the display head. The navigation computer, sensor controller, RF modem, GPS receiver, and CD-ROM drive were all mounted in the trunk. The computer booted automatically whenever the ignition was turned on (as one might expect, shut down was performed when the ignition was turned off). A push button under the vehicle dashboard could be used to reboot the computer on demand.

The navigation computer was designed to meet the specifications of the automotive environment, normally -40° to $+85^{\circ}\text{C}$ (-40° to $+185^{\circ}\text{F}$). In the ADVANCE implementation, the allowable operating temperature range was -30° to $+70^{\circ}\text{C}$ (-22° to $+158^{\circ}\text{F}$) and allowable storage temperature range was -40° to $+85^{\circ}\text{C}$ (-40° to $+185^{\circ}\text{F}$). Most parts used for the computer can operate up to $+105^{\circ}\text{C}$ (221°F) to allow temperatures to rise inside the enclosure. The operating humidity limits were 8% to 80% and storage humidity limits were 8% to 95%. As far as vibration was concerned, the computer could withstand a total 10-min duration of sweeping from 15 to 60 Hz in 5 min then back to 15 Hz. As far as shock limits were concerned,

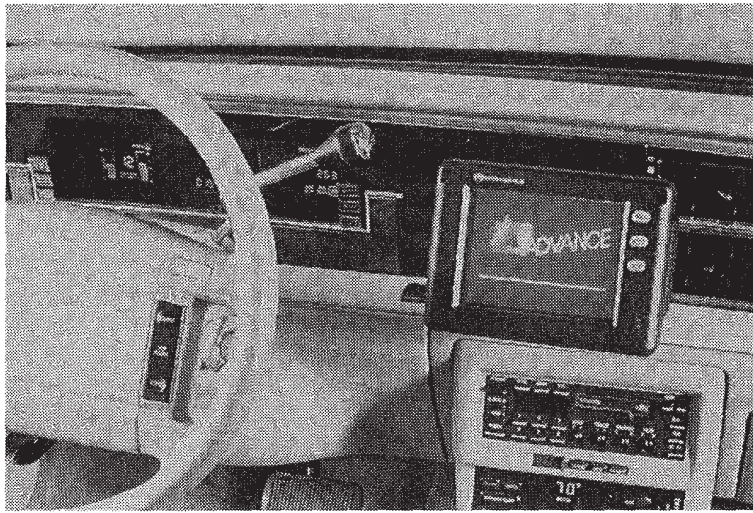


Figure 11.6 In-vehicle MNA display unit.

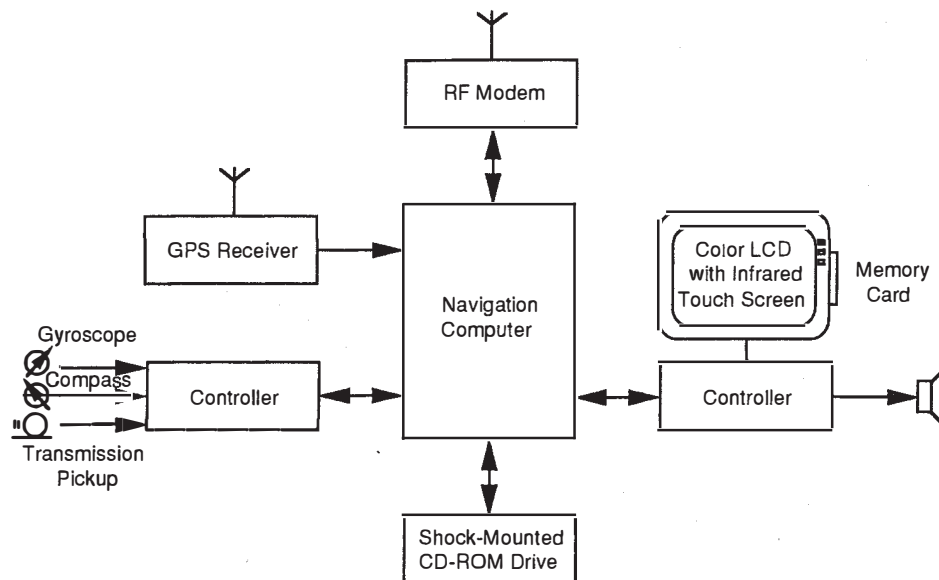


Figure 11.7 In-vehicle MNA hardware configuration.

the computer could be dropped from a height of 75 cm in a packing carton onto a concrete floor to strike one corner, three edges, or six faces without damage. The operating voltage was from 10.5 to 16V, with a nominal voltage of 14.4V and current of 3A. During startup, it could withstand a voltage of 24V for 2 min.

The touch panel (touch screen) was based on infrared technology. As we saw in Section 7.2.2, this technique has negligible effects on contrast. Evaluations indicated that infrared touch panels had lower glare and better brightness than resistive touch panels in daylight. A backlit color LCD was used as the display unit. The LCD used active-matrix addressing. The size of the screen was 15 cm (5.7 in.) on the diagonal. The size of the display unit was 17.8 × 12.7 × 6.4 cm (7 × 5 × 2.5 in.). The allowable temperature range was similar to that of the navigation computer. The power supply was 12V at 1A maximum.

The majority of user data entry to the navigation system was performed via the touch panel. Besides the soft (touch) keys on the screen, there were three hard keys on the right side of the monitor that were used for additional controls. The MAIN key was used to display the main screen choices as shown in Figure 11.8. When the car icon on the screen was pressed, the previously stored destination was displayed. If none were stored or the driver wanted to plan a new trip, two choices for method of destination entry would be displayed: by address or by intersection. A keyboard-like touch screen was displayed for entering state names, city names,

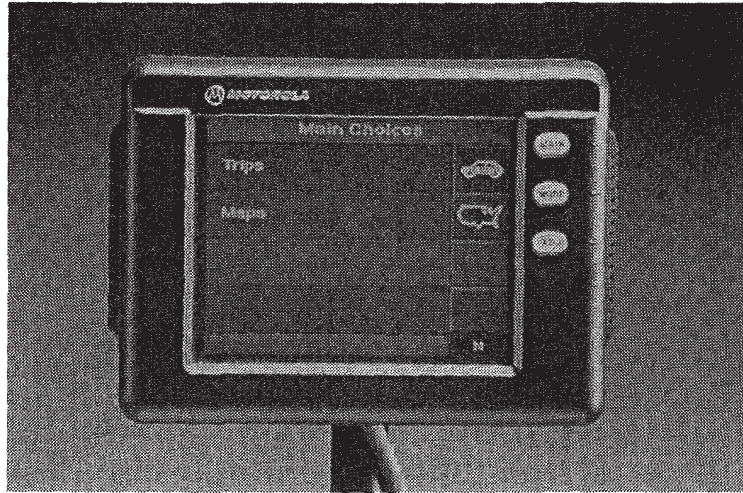


Figure 11.8 Driver interface.

street names, and addresses. If the map icon was pressed, the road network surrounding the vehicle would be displayed as shown in the route map display later. The "MORE" key was used to display an additional menu, which could be used to enter personal information and show system status information such as the current location. The ADJ key was used to mute or adjust the speaker volume and screen brightness. The current travel direction of the vehicle was displayed using letters (i.e., N, E, NE, NW, etc.) in the lower right corner of each screen. The direction was also indicated by a triangle when the system was in map-display mode.

During the trip, the screen could be in either one of two modes to show the user the current trip status. One display mode used the turn arrow format shown in Figure 11.9. The other mode used the route map format shown in Figure 11.10, which basically consisted of a simplified route map on which the planned route was not highlighted. Recall that we discussed the advantages and disadvantages of these formats in Section 7.2.3. Because most of the touch functions were automatically locked out for safety reasons when the vehicle was in motion, no planning of new routes to unstored destinations could be made until the vehicle was stopped. This user lockout was used to prevent the user from interacting with the interface while driving.

Both display formats showed the name of the road that the vehicle was currently on at the bottom of the screen and the name of the next cross road at the top of the screen. In the turn-arrow format, there was a countdown bar on the left-hand side of the screen with a decreasing mileage number and a shrinking red rectangle. The user could review the summary information for the trip or a list of series of

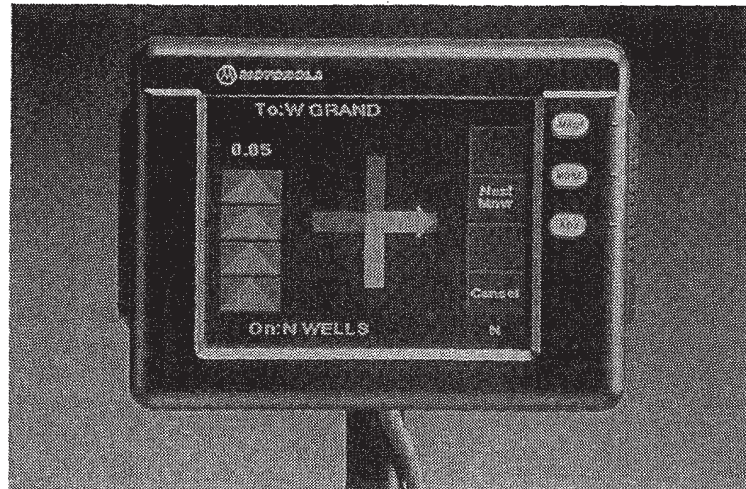


Figure 11.9 Turn arrow display.



Figure 11.10 Route map display.

upcoming maneuvers at any time by touching the right-hand side of the touch panel. The turn arrow was displayed in yellow and superimposed on the intersection (which was displayed in gray). In the route-map format, a map was displayed to show the area in the immediate vicinity of the vehicle. A red triangle with a white boundary indicated the current location of the vehicle and also the direction of the vehicle as determined by the map-matching-based positioning system. A filled green circle (dot) indicated the location reported by the GPS receiver. If the circle had an orange boundary, this indicated that the DGPS correction was in effect. A yellow dot was used to warn the user that the GPS signal was being received from less than three satellites, with a corresponding reduction in position accuracy. The user could choose also to zoom in or out on the map.

The display monitor could be rotated. Because of the limited viewing angle of the LCD and the need to avoid direct sunlight, this feature was required in order to provide the user with the freedom to rotate the monitor to a comfortable viewing angle.

The MNA used a RAM-based PCMCIA memory card to store traffic data. These data were similar to the data reported back via the COM subsystem. The minor difference was that occasionally a probe report might not be able to reach the TIC. For instance, since U-turns rarely occurred and rarely affected the travel time, this information was not sent to the TIC via the wireless network but kept by the memory card. The information stored in the memory card could be accessed by the TIC later using a card reader to validate and supplement the data received by the TIC via the COM. A 2-MB (formatted to 1.44-MB) static RAM memory card with a memory backup battery was used for this project. It had an operating temperature range of -30° to $+70^{\circ}\text{C}$ (-22° to $+158^{\circ}\text{F}$), the same as the navigation computer.

The CD-ROM drive was shock-mounted on top of the navigation computer as shown in Figure 11.11. The user could change disks by opening the drive cover. The drive had an operating temperature range from -30° to $+60^{\circ}\text{C}$ (-22° to $+140^{\circ}\text{F}$). During the field tests, the upper range became a problem. On some days when the trunk temperature reached 70°C (158°F), drive performance was erratic since the operating temperature limit had been exceeded. The power supply was 12V. The CD-ROM had a total capacity of 600 MB and its drive had an approximate transfer rate of 150 Kbps. The drive was connected to the navigation computer via a SCSI port.

The positioning sensors were wired to the navigation computer in the trunk. A fluxgate magnetic compass was used to measure the absolute direction of the vehicle. It was either installed in back between the headliner and the outside roof of the vehicle (Figure 11.5) or on the windshield behind the rearview mirror. (Note that the compass should be installed in a location that will minimize abnormal magnetic effects on the measurement.) The power supply voltage range for the compass was 10 to 15V dc, with a typical voltage of 12V. The maximum power supply current was 150 mA. The range of operating temperatures for the compass

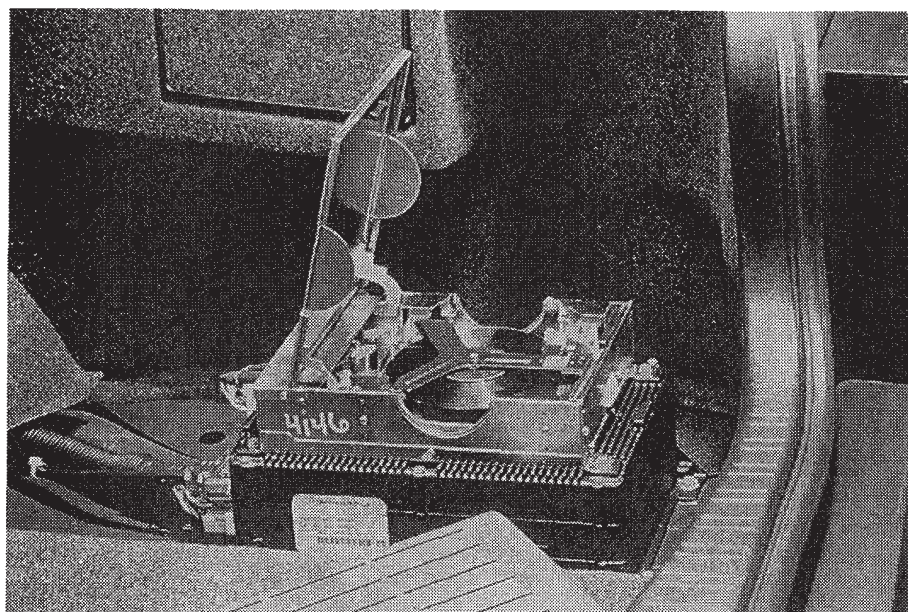


Figure 11.11 Navigation computer and CD-ROM drive.

was slightly better than that for the navigation computer. A vibration gyroscope with a triangle bar was used to measure the relative direction of the vehicle. It was installed in the side wall of the trunk. The gyroscope must be installed perpendicular to the vehicle's direction of motion with the base glued to a spot with minimum vibration. The gyroscope had a power supply voltage of 8 to 13.5V dc and a maximum power supply current was 15 mA. The gyroscope had an operating temperature range of -20° to $+70^{\circ}\text{C}$ (-4° to $+158^{\circ}\text{F}$). Distance was measured using transmission pickup sensor. Either a variable-reluctance sensor or a Hall-effect sensor was used, depending on the vehicle model. A variable-reluctance sensor will produce a sine-wave output, whereas a Hall-effect sensor will produce square waves of constant amplitude. A detailed discussion of the operating principles and characteristics of these sensors can be found in Section 3.3.

The GPS receiver and the RF modem were both mounted in the trunk. Their operating temperature ranges were similar to those of the navigation computer and both operated from 9 to 16V dc power supplies. They were both connected to the navigation computer using RS-232 cables. As we saw in Section 3.4.2, the GPS receiver functions as an absolute sensor to report vehicle position, direction, and speed to the navigation system. The RF modem was used to receive the link travel time updates and DGPS correction messages from the TIC and to transmit the current link travel times back to the TIC. This device had a single circuit board which included both a two-way data radio and a modem with a 3W transmitter. To avoid interference, the GPS antenna and the RF antenna were separated by at least 0.914m (3 ft).

11.3.2 Software

Because of the real-time and embedded nature of the MNA software, a multitasking real-time operating system was used. To better service the application layer, an operating system services (OSS) layer was constructed on top of the kernel (Figure 11.12). The kernel was the central piece of the operating system that interacted with the computer hardware. The purpose of this OSS layer was to isolate the applications from the host kernel dependencies and provide increased portability to other platforms. The main functions of this layer included the following:

- System initialization and synchronization;
- System shutdown;
- Memory and time management;
- Navigation device driver management;
- Interprocess communication via messaging;
- Mutual exclusion via semaphores;
- Interprocess synchronization via events; and
- Error handling.

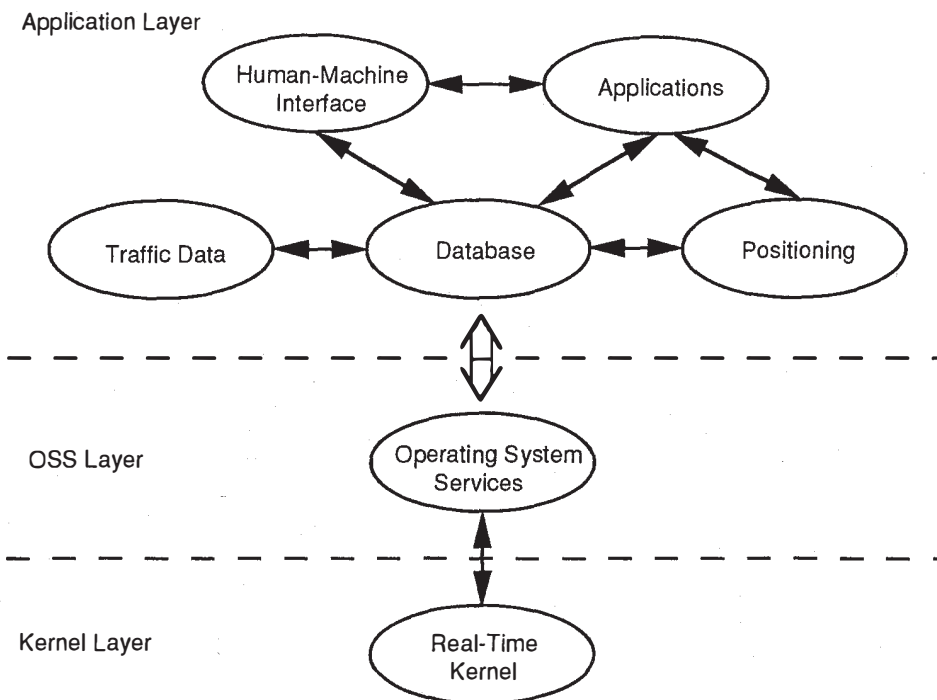


Figure 11.12 Main MNA software processes.

The main sequence of execution in this layer was as follows: Create the tasks, set up the memory buffers and disk caches, create the message queues, system semaphores and events, start the tasks, loop and monitor system events, and coordinate system shutdown when required.

The ADVANCE in-vehicle navigation system consisted of all seven basic building modules we learned about in Part I. The software must support the full functionality of these modules. Figure 11.12 shows the main MNA processes. To save space, two-way interprocess communications between processes are indicated using lines with arrows at both ends. A process may consist of more than one task. To avoid cluttering the diagram, a wide double-ended arrow is used to indicate that all the processes in the application layer interact with the layer below, that is, the OSS process. Once the driver has started the vehicle, the navigation computer began initialization and jumped to the execution sequence described in the end of the last paragraph. Once all tasks had started running, the system was ready to accept user input and requests.

Both the structured and object-oriented methodologies were used in the software analysis and design. Because of the variety of tasks involved, this approach

provided flexibility to each individual software engineer or team for their own development efforts.

Message passing was the main primitive used for interprocess communication among tasks, with message queues as the communications medium for passing the messages. Two other interprocess communication primitives were also used to support mutual exclusion and synchronization. Mutual exclusion is a way to ensure if one task is using a shared variable or file, the other task will be prevented from doing the same thing [8]. The map data cache is one example of an object that different tasks may want to have read and write access to at the same time. The other two primitives used to support mutual exclusion and synchronization were semaphores and events. Semaphores and events are special variables (or system calls) reserved to report the status of shared variables or files to tasks that need to access them.

We now briefly discuss each process in the application layer. The database process responded to all read and write inquiries from other processes. A hierarchical digital map database was constructed for the MNA. The main reason for using this hierarchical database was to speed up route planning. Because the map data were stored on CD-ROM (which is a device with relatively slow retrieval speed), a cache was implemented in main memory to store frequently accessed data. A database manager was responsible for controlling access to this cache. Different data retrieval inquiries may need to access parcels of data in different layers. Only the route planner was required to have access to parcels in higher layers. All the other modules accessed the lowest layer parcels. As we saw in Part I, this speeds up the time-consuming route-planning process. As defined in Section 2.6.3, a parcel is analogous to a portion of the map area, and is a collection of geographical objects (such as segments) that fall within a rectilinear region defined by minimum and maximum latitudes and longitudes. The dynamic database task received link updates from the TIC and updated the relevant link data stored in main memory (Figure 2.10).

The positioning process included sensor polling, and various integration tasks, as well as a map-matching task. It polled the sensors and fused the resulting data, which were then matched against road segments on the map using a probabilistic method. Once the matching process was complete, the current position and direction of the vehicle were output to the application process and used as inputs for the route-following task and also forwarded to the human-machine process for display on the screen.

The traffic data process was used to log the current link-related travel data. One copy of the log was stored on the memory card. Another copy was sent via RF modem and the COM subsystem to the TIC as a probe-vehicle report. These data (fused with other data) were used to generate predicted travel times for the TIC to broadcast to all test vehicles in the test area. The other data used for fusion here included loop detector data and anecdotal information.

The human-machine interface process was an event-driven process. All other tasks were required to communicate with it via messages. This process first converted the queued message to an event and then processed the event. No blocking was allowed while processing the event. After message conversion, an event queue was used for prioritization. The design and implementation of this process is very important, because it is the one that most affects users' impressions of the system. Figure 11.6, Figures 11.8 through 11.10, and Figure 11.13 show samples of the graphical user interfaces implemented within this process. A detailed discussion of the human-machine interface module can be found in Chapter 7 and the references contained therein.

The application process interacted with other processes and provided many valuable services to the system:

- Planning routes under the shortest time criterion;
- Generating maneuvers for planned routes;
- Supporting maneuver previewing for planned routes;
- Supporting travel distance display;
- Guiding the vehicle along a planned route;
- Supporting on-demand off-route recovery;
- Using dynamic information received from the TIC to replan routes;
- Forwarding current vehicle location and motion status to the human-machine interface.

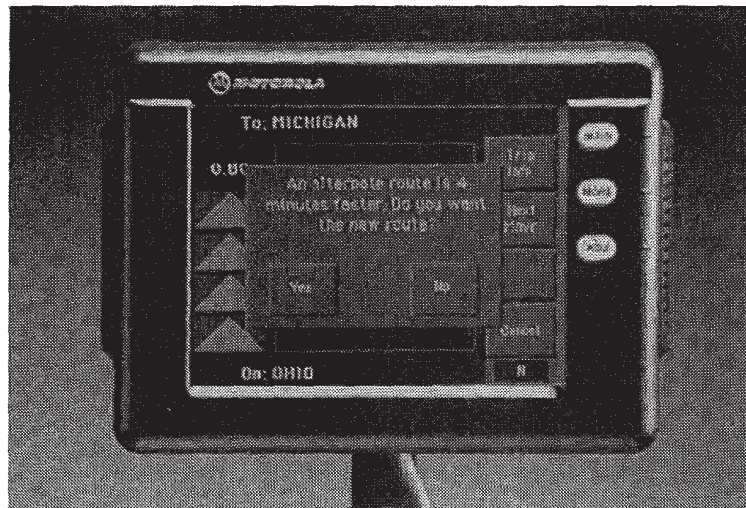


Figure 11.13 Typical display during dynamic navigation.

All of these services were provided by different tasks. The two most important tasks were route planning and guidance. The planning task was based on a bidirectional hierarchical heuristic search algorithm. The evaluation (cost) function of the algorithm was based on the travel time. During route planning, an update message was displayed on the screen to indicate what percentage of the planning had been completed. Once the route was planned, the route segments were then passed to the route guidance module. First, each higher layer segment was broken into segments at the lowest level, and maneuvering information such as turn types and maneuver types was added (Figure 6.2). The result was a maneuver list that the route-following task could follow using the position information provided by the positioning process. This module also periodically sent messages to the human-machine interface module to identify the next set of instructions to be fetched from CD-ROM to main memory. This allowed the human-machine interface to provide turn-by-turn prerecorded human voice instructions to guide the driver. One important feature of this process was that a better route could be planned whenever the route-planning module discovered that a link cost on the planned route had been updated. The route-planning module replanned the route based on the newly updated link travel time. After completion, it would compare the new route against the original route to see if the new route was better. If the new route had at least a 2-min time savings compared to the original one, it would pop up a window on the display unit and unlock the screen to ask if the user wanted to take this new route. Both the visual display and voice were activated to remind the user. Figure 11.13 shows a typical dialog box. If the user accepted the new route, the original route was deleted and all route guidance activities were transferred to the new route.

One interesting challenge that the project faced was how to make the road segments used by the MNA compatible with the links used for travel time updates by the TIC. The MNA static database represented the road network using nodes and segments (recall that these terms can be found in Chapter 2). In contrast, the TIC used links to represent the dynamic travel time information associated with the corresponding segment (recall from Chapter 6 that a link is a segment plus a turning movement). The link cost is the travel cost of the corresponding segment plus a turning cost. If we used geographical coordinates (latitude and longitude) to match links with segments, the message would be much longer, and RF capacity would be wasted. A simple way to solve this problem is to assign a unique identifier (ID) to each link and associated segment. One naming algorithm first assigned sequential IDs to all nodes in the test area following a predetermined assignment pattern [9] (recall that a segment is a piece of roadway between two nodes). After the node assignment, the segment could be represented by a unique pair of IDs identifying the end nodes of the segment. The algorithm then assigned unique IDs to each link to match pairs of segment IDs. These unique IDs were used to identify links in communications messages. After these messages were received, the MNA then used these link IDs to locate the relevant segments for updating the dynamic database.

Meanwhile, the MNA transmitted probe report messages to the TIC. These probe messages included link descriptions and link costs converted from the corresponding segment IDs and travel times.

The reader may have already noticed that the combinational effects of the processes discussed form a well-structured dynamic navigation system functionally equivalent to that shown in Figure 1.3 of the introductory chapter. As mentioned in Section 10.3.2, the various functions implemented in the application layer are a vivid result of integrating the basic modules (building blocks) we studied in Part I. Once the individual location and navigation modules have been completed, it will be much easier to use these modules or variations on these modules to implement a completely new, stand-alone system.

11.4 COMMUNICATIONS NETWORK

Since the communications network (COM subsystem) was a significant component of the ADVANCE project, design requirements were established early in the development that:

- Restricted communications development to a minimum;
- Covered the defined test area;
- Provided communications for a fleet of 5,000 vehicles (later reduced to 80 vehicles for targeted deployment);
- Provided two-way communications;
- Provided for staged growth;
- Provided messaging that was not critical to public safety;
- Provided real-time communications;
- Supported point-to-point inbound and broadcast outbound communications.

Based on these requirements and the available technologies, the full system was constructed using a phased development methodology.

The Motorola Data Communication (MDC 4800) system was selected for the COM subsystem used during the targeted deployment phase of the project. This is a private land mobile radio system using a central dispatch approach. It consisted of an infrastructure at a central location that provided two-way communications for participating vehicles. Each of the probe vehicles could initiate or respond to the central station. The system configuration is shown in Figure 11.14, where P-A stands for preamplifier and M stands for modem. The COM subsystem and TIC could be physically located at the same site or at two separate sites, as was the case for the ADVANCE system.

The COM site was housed in a 59.44m (195 ft) high leased facility in the south central portion of the test area. This site was chosen because RF coverage

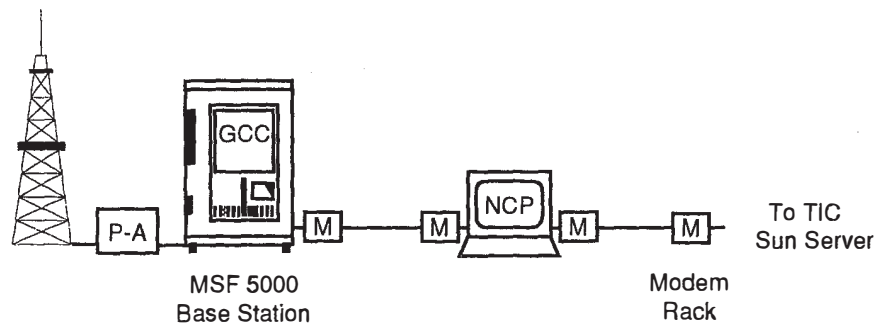


Figure 11.14 RF COM infrastructure.

prediction studies indicated it provided the best coverage to the ADVANCE test area. The site consisted of an MSF 5000 800-MHz base station, a General Communications Controller (GCC), and a preamplifier transmitting on 853.0625 MHz into 12-dB gain for outbound messages and receiving on 808.0625 MHz transmitted at 3W into 3-dB gain for inbound messages. The GCC is a processor that encodes and decodes various communications protocols. The base station and GCC were housed in a 122- × 55.88- × 58.42-cm (48- × 22- × 23-in.) cabinet and the preamplifier was housed in a 45.72- × 7.62- × 20.32-cm (18- × 3- × 8-in.) cabinet. The base station can support three channels. For this field deployment, only one channel was used for both transmitting and receiving. It was connected (via the preamplifier) to the antennas with 56.4m (185-ft) runs of 4.13-cm (1-5/8-in.) diameter Heliac. The antennas (DB810K-XT) were omnidirectional and had 10-dB gain. Through modem connections, data could be transmitted over a leased telephone line to the NCP (network control processor) at the TIC. The NCP can route messages for up to 16 base stations. Therefore, the NCP could support a maximum of 48 channels. Further evaluation concluded that the test area had good data communications coverage [10]. The actual coverage was 99% (which was higher than the 90% design requirement).

For efficient utilization of resources, the one-on-one transactional messaging was eliminated for the outbound channels, while a one-to-many broadcast approach was used by the base station. By broadcasting the outbound messages, message acknowledgments and individual addressing were eliminated from the communications protocol. Identical messages were broadcast on the outbound channels, while individual inbound messages were transmitted on the inbound channel from each probe vehicle to the base station. A one-to-one transactional messaging protocol was still used for these transmissions. Probe vehicles were divided into groups locked onto a given pair of inbound and outbound channels. No roaming was allowed among inbound channels, in order to facilitate staged growth of the system. All messages were encoded in binary form, with a maximum of 240 bytes for each

outbound message and a maximum of 50 bytes for each inbound message. This shorter, 50-byte message length increased the possibility for each probe message to reach the COM subsystem. Two inbound-message throttling methods were designed in order to prevent runaway lengths and to ensure that communications could be maintained under severe overload conditions. To further limit the communications traffic, travel time information for residential streets was not sent over the air. The maximum number of retransmissions for inbound messages to the TIC was limited to four. Because the base station had a power of 100W and mobile transceiver power had a power of 3W, every received signal was amplified 10 dB before being processed in the base station.

The COM subsystem was connected to a modem in the TIC server modem rack over a leased telephone line via an NCP as shown in Figure 11.14. The leased line had a transmission rate of 9600 bps. As we mentioned earlier, the COM subsystem handled both the inbound and outbound data flow. The travel time predictions and other pertinent data generated by the TRF were sent to the probe vehicles via the COM subsystem. In return, the COM subsystem received current travel times from each of the probe vehicles. The implementation of the communications interface protocol conceptually followed the ISO OSI Reference Model shown in Figure 8.10.

With the broadcast architecture, binary message encoding, inbound message throttling, and reduced number of link-update messages, 20 MDC 4800 RF channels would be required for a fleet of 5,000 vehicles. This was not feasible under the architecture discussed previously. An alternative 19.2-Kbps protocol (RD-LAP; see Table 8.6) was investigated to replace the MDC-4800 protocol; this would have required no changes in the TIC and MNA. This alternative would have reduced the number of RF channels from 20 to 3. Because there were no RD-LAP modems available to accommodate the ADVANCE project schedule, other technologies were evaluated such as ARDIS (Section 8.3.5) and broadcast subcarriers (Section 8.3.6). Eventually, a COM design that could support up to 5,000 vehicles in the area (for later phases in the project) was completed. The new system was based on the iDEN 64-Kbps communication system (Section 8.3.4). The most important feature of the iDEN option compared to the RD-LAP was the higher data rate, so that only two RF channels were required for the 5,000 probe vehicles. Due to the targeted deployment, this version of the COM was never deployed into the field, although operational test results indicated that this system worked extremely well.

A great deal of useful experience was obtained during implementation of the COM subsystem. For instance, most commercially available one-way or two-way RF communication systems are optimized for a high number of individual transactions. By contrast, in the COM architecture, outbound messages were broadcast continuously whereas inbound transactions occurred only occasionally. This unique architecture required modifications of available off-the-shelf equipment. Furthermore, commercial equipment is often designed for certain radio bands. Unfortu-

nately, these bands are saturated in most metropolitan areas. Therefore, careful evaluation must be made before selecting a suitable RF transmission product.

ADVANCE was successful in achieving the major field-test objectives established in the early 1990s. During the course of project development, many challenges were encountered [11]. However, many useful lessons were learned. Some late requirements added to support operational field testing significantly affected system design, and resulted in the system discussed in this chapter. One example was the decision to record detailed traffic data for postevaluation. The earlier design had to be changed or modified along the way in order to incorporate new hardware and software for this additional feature. Despite incremental changes for tailoring the system to satisfy many different expectations proposed by all interested parties, the major goals were achieved, and deployment and evaluation provided many valuable results.

11.5 INITIAL EVALUATION RESULTS

As of this writing, final evaluations of the ADVANCE project are still under way. We first discuss some of the initial findings and then direct readers to references for the upcoming final results at the end of this section. Before turning our attentions to these findings, we first consider the major evaluation objectives of this project, which will help explain the origin of these and other findings. The evaluation included the innovative features of the system, in particular the concept of vehicles as traffic probes. It emphasized the following:

- Evaluation of TIC for meeting the present and future needs of the partners involved in the project;
- Assessment of TRF and probe vehicles versus loop detectors for collecting real-time traffic data;
- Determination of whether in-vehicle route guidance can be beneficial in avoiding urban congestion for familiar drivers;
- Examination of the effectiveness of dynamic route guidance in reducing travel times;
- Summarizing of the achievements and lessons learned;
- Review of institutional arrangements for future efforts.

Because the targeted deployment involved fewer probe vehicles than originally planned, the field tests were conducted in a more controlled environment. This enabled the participating parties to evaluate well-defined characteristics of the system more accurately. On the other hand, this approach might also hinder the ability to test the robustness of the system to handle uncontrolled random and emergency situations as well as much larger fleet dynamics. In addition, the data collected by

the probe vehicles were not sufficient to model the traffic flow over the entire road network in the test area.

Before drawing any conclusions from the initial findings discussed here, we would like to remind the reader that all of these results were based on one particular system tested in one particular test area under certain restrictions. For instance, the system did not provide any traffic information for local streets. The road network in the test area is generally a regular rectilinear arterial grid, which makes it difficult to provide far more efficient alternative routes. Test drivers were familiar with the road network and voluntarily participated in the evaluation. During the evaluation, it was discovered that the system was effective in reporting traffic emergencies and directing drivers to alternative roads. This was particularly helpful for highway travelers. Incremental improvements were made in the dynamic database, network model, and historical profiles (travel time files) during the deployment period.

The study found that reasonably accurate travel time predictions for the upcoming 15 min on a link can be provided by at least three probe vehicles that have just traversed that link over the preceding 15-min period. Because the loop detectors were placed to operate a "closed-loop" signal system, information from these detectors was of marginal value in traffic congestion measurement. Probe reports provided more accurate estimates of travel time. These insights were based on more than 50,000 probe reports, of which 99.4% were reliable.

Nearly 100 origin-and-destination runs were conducted to compare the performance of static and dynamic navigation. Test vehicles were divided into two groups traveling on the same route: One without real-time traffic data and the other with real-time traffic data. Only occasionally were large time savings found. On the other hand, the number of test runs available on any particular route was generally too small to obtain statistical verification of significance.

The evaluation team found no strong evidence from the available test runs that real-time traffic data could make a significant impact in reduction of users' travel time and improvement of performance on arterial roads. The reason may be that familiar drivers are often able to avoid traffic congestion or trouble spots by driving on alternative roads, frequently on residential streets, or by relying on radio traffic reports. In contrast, community standards may be infringed by excessive routing to residential streets; this was reflected in the ADVANCE route planner. Another possible reason is that traffic flows on arterials are mainly determined by turn signal timing. The latency of real-time traffic data arriving at the vehicle is not so large as to affect dynamic route guidance. The turning movement information included for guidance did not seem to lead to any noticeable decrease in travel time or have any significant impact on the system as a whole. There was no significant difference in time savings from incorporating the delays for left turns, straight-through turns, and right turns. The system was effective at saving the traveler's time on highways, perhaps because there are only a few entry and exit ramps on these long roads. Similarly, the unimpeded nature of highway traffic allowed the collected

data to represent the highway network more accurately than the network of arterial roads.

The ADVANCE operational field test focused on drivers who were familiar with the road network and communities in the test area. The initial findings from the survey responses to the dynamic route guidance systems led the evaluation team to conclude that they had different needs and desires than unfamiliar drivers, such as visitors, who may be more concerned with obtaining accurate directions than saving travel time [12]. Familiar drivers expect a more intelligent navigation computer that can incorporate their knowledge or learn from their experience, rather than simply being told where to go by a predetermined algorithm. This finding was obtained from a small fleet driven by familiar drivers with very little real-time traffic data available to support the dynamic route guidance, because the entire test field had at most 80 equipped vehicles in addition to the loop detectors and anecdotal information. The 2-week test period was relatively short. All ADVANCE test drivers were volunteer members of households [13]. Most households had incomes of more than \$50,000 per year and had two or more motor vehicles. The mean age of the drivers was 44 years, and 62% of them were males. This sample is biased compared to a random sample of the population.

A focus group study of 32 ADVANCE test drivers found that drivers were more interested in dynamically updated traffic information than a route planner that uses static information. Database errors and the fixed criteria for route selection and planning meant that the quality of planned routes was not sufficiently high. Participants wanted more control over the planning process and the flexibility to choose planning criteria. Some preferred to be presented with more than one route. Participants suggested that a route planner probably should learn from the daily routes taken by the driver. Real-time traffic data could be used to evaluate these routes so that faster alternatives could be generated if necessary. Participants believed that drivers would be willing to pay for future real-time route guidance systems and services. Some were willing to pay from \$750 to \$1,000 for an in-vehicle unit in addition to from \$2 to \$30 per month for "single-area" coverage of real-time traffic data.

One hundred and ten drivers returned the follow-up survey after the field test. In the survey, they rated the importance and performance of 13 system features. Destination accuracy, route quality, system reliability, route-planning performance, and tracking accuracy received the highest scores for importance of features (Figure 11.15). Of these, route quality and route-planning performance were rated the features with lowest performance. Responses to the willingness-to-pay-for-future-route-guidance-systems question were in the range of \$500 to \$2,000, with mean price of \$980. All these findings suggest that a more intelligent route planner may be required in order for in-vehicle guidance systems to attract familiar drivers to the market. It has been speculated that U.S. car rental companies may be the largest buyers of static navigation systems at this point because most rental car drivers are

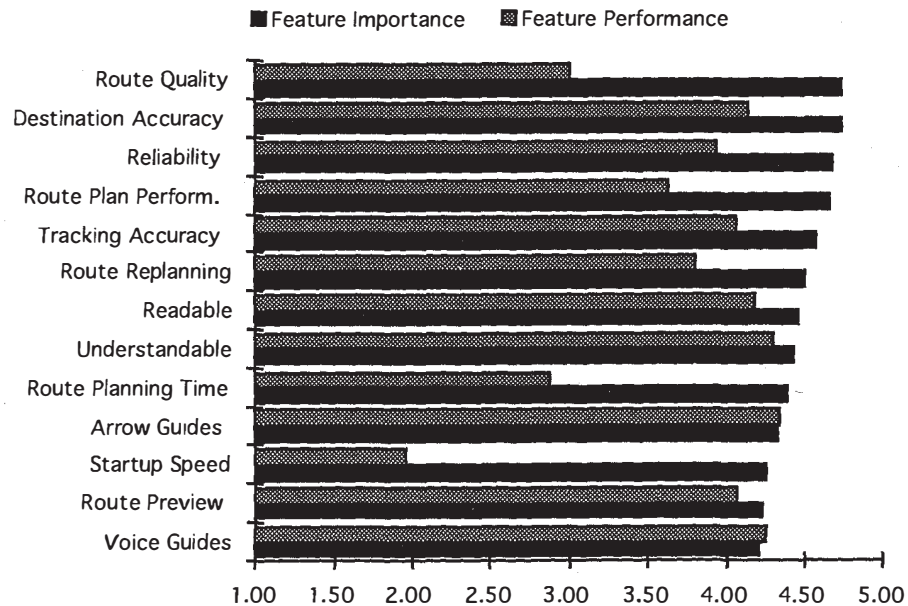


Figure 11.15 Familiar drivers' ratings of ADVANCE guidance features (Source: ADVANCE project.)

unfamiliar with the area in which they are driving and their priority is to follow well-presented routes to reach their destinations.

Questions remain with respect to the cost of the two-way communications equipment and airtime. This question must be answered before massive deployment of this type of system can occur. Periodically reporting traffic data back to the TIC takes significant airtime. If the vehicle owner were responsible for the entire payment, few would be willing to purchase this communications equipment.

The limited evaluation results seem to suggest that dynamic route guidance will enjoy only mixed success without instant real-time traffic data updates. It is very likely that a successful system will have to be able to detect and respond to large and unexpected delays on the network and provide more intelligent assistance to drivers. Because small savings in travel time may not be enough to convince familiar drivers to follow the guidance suggestions and to purchase the unit, more studies and research must be done to ensure that such systems can meet the expectations of the general public, especially familiar drivers.

Interested readers can obtain more information about this project from the ADVANCE Internet WWW page [14], which points to all available technical documents, working papers, and reports. A series of white papers should be available

there by the time this book is published so that readers can study final evaluation results.

Let us consider one question to conclude this chapter. The ADVANCE system was designed in the early 1990s. With the location and navigation modules you learned and the new technologies available right now, could you design a dynamic navigation system that achieves the same functionalities as ADVANCE, but with much more efficient performance and cost-effective components? More simply, can you improve any one of the subsystems or components described in this chapter?

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CHAPTER 12



CONCLUSIONS

As we have seen, development of a location and navigation system is not a simple task. However, with the broad background and technologies studied so far, we should be able to make this task much easier. In other words, we need to properly identify system requirements, determine the system architecture, identify the functions to be supported, specify the corresponding modules, and select suitable hardware components and software tools to design and implement these modules creatively based on the principles learned in this book. Furthermore, we need to test and integrate these modules into a flexible, expandable, and compatible system. We have learned that a variety of modules can be implemented (Part I) and different systems can be constructed on the basis of these modules (Part II). In particular, studying Part II has provided us a better appreciation of the intricacies of systems engineering. As we mentioned at the beginning of this book and will discuss in a later section here, without proper system-level design, systems may have deficiencies that can be difficult to correct even if the modules are individually functional. We conclude this book with a discussion of lessons learned from past experience and possible future directions for vehicle location and navigation systems.

12.1 PAST LESSONS

The discussion in this section focuses more on engineering-related than on other issues such as funding, marketing, policy, legal, and private-public partnerships,

which have also arisen in the past. Interested readers can find discussions of those types of issues in the proceedings of conferences organized by European Road Transport Telematics Implementation Coordination Organization (ERTICO), Intelligent Transportation Society (ITS) of America, and VERTIS (Vehicle, Road and Traffic Intelligence Society, Japan).

Good market forecasts are required for development of any location and navigation product. Different markets may have different cultural backgrounds, environmental issues, and different types of driving (rental, commuting, shopping, etc.). Compared with the Japanese in-vehicle navigation market, the European and U.S. markets are still in the early stages of development. As stated in Chapter 1, according to Japan Electronic Industries Association, sales of vehicle navigation systems to consumers in Japan reached 530,000 units in 1995, up 73.2% from 1994. More than 30 companies are competing in a market that has seen prices of some units drop from U.S. \$6000 eight years ago to around \$1900 today. In Japan, addresses are based on land sectors or on the order of construction, rather than location on a street. Only major streets are named, and most small streets have no names. Therefore, map drawing and reading are essential skills for survival in Japan. Directions are often given using major landmarks on maps rather than street names, traffic lights, and stop signs. With this cultural background, it is not difficult to understand why the map-display-based navigation system has been very well embraced on the Japanese market. The method of navigation in Japan is to superimpose a route on the map and guide the driver to an area close to the destination. On the other hand, in the United States and in European countries, every street has a name and every building or house has an address, with the special case that many major European cities have quite a few traffic circles. The navigation usually relies on turn-by-turn instructions to guide the driver to a specific address. Furthermore, in the United States, people are more concerned about their personal safety and the safety of their vehicles and less worried about finding a location (because of their addressing system is relatively easy). These cultural and environmental differences imply quite different attitudes toward navigation products.

In the United States or Europe, a vehicle navigation system often provides turn-by-turn guidance. It is important for such a system to have a large main memory, a fast database access storage device, and a powerful CPU. Even with a fast, large memory and a high-performance CPU, better data structures and algorithms are still required to increase the speed of the system. On the other hand, powerful graphics processing is essential for the rapid map-scrolling and scale-change features found in Japanese navigation systems. Although the distinction may not be very clear, map-display-oriented navigation systems often need more graphics processing power while turn-by-turn-oriented navigation systems require rapid route calculation and real-time guidance response. Without any question, a product would be successful on the U.S. and European markets if it could be developed to maintain a low selling

price and comfortable profit while providing both sets of features. However, this is easier said than done. Products should probably first target a specific market segment.

A stable and accurate map database is required to develop a quality navigation system. This database can help improve system accuracy and reduce subsequent modification of the navigation software. Many features of the display and traveler information (human-machine interface), positioning, map-matching, route-planning, and route guidance modules rely on database attributes, including road type, maneuver type, turn type, street speed, street name, etc. Any database changes could result in a significant reengineering effort to rebuild the navigation system.

Project managers or lead engineers must be willing to take a concrete step-by-step approach starting from the basics, to have good interpersonal skills and a broad background, to learn new technologies, and to have faith and stick with the project in order for it to be successful. Any work on a new subsystem, prototype, or product should start with the basics. In other words, it is better to make it as simple as possible but make sure it works correctly and is expandable from the very beginning. Any new features or enhancements can then be easily added to a working system. As discussed in the beginning of Part II, a good system architecture is essential to providing a stable basis for any expandable and flexible system. For a complex product that involves both hardware and software, there must be an experienced systems engineer (architect) or a team of systems engineers to coordinate design and development. Otherwise, costly testing and integration as well as temporary patches could mean more trouble later while trying to push a product out the door for a delivery deadline. However, even a good system architecture is normally only suitable for a limited range of system sizes. A completely new kind of problem should be expected every time the system is enlarged by a factor of two. Software engineers should be involved from the beginning of the design phase to avoid the necessity of tailoring code to already finished hardware. It is always worthwhile to spend more time on the system specifications. Finally, the managers and engineers involved in any location and navigation project must keep faith in the project, which is equally important to learning new technologies. A firm belief in the project, persistent effort, and full support from upper-level management, especially during difficult times, are critical for any success.

A thorough understanding of software project management and the development life cycle is particularly important because there are so many critical programs embedded in the location and navigation system. Software project management is also an engineering discipline in its own right, with predictable patterns. Many experts believe that a software organization or development team should use the capability maturity model (CMM) developed by the Software Engineering Institute (SEI) to measure the maturity of the organization [1]. SEI is a federally funded research and development center that is affiliated with Carnegie Mellon University in the United States. The higher the SEI maturity level a software organization has, the better a software product it can produce. Even using the CMM, many of the

system-level issues involved in a complicated embedded multitasking system require experienced and dedicated engineers.

Configuration management should be adopted at the very beginning of the project. Configuration management is a process to maintain the integrity of products as these products evolve through the development and production cycles [2]. It identifies, controls, and provides the status of defined hardware, software, and firmware end items. Software configuration management is especially useful for mission-critical software development projects involving teams of developers. Through documenting and tracking software during its life cycle, software configuration management ensures that all changes are recorded and that the current state of the software is known and is reproducible [3]. In addition, all project-related documents should be placed under configuration management. After all, this is a vital component of product quality management and a key to maintaining competitiveness in today's global marketplace.

When selecting software methodologies, both managers and engineers must understand the pros and cons of the various methodologies available. In particular, correct assessment of available methodologies is very important for any real-time embedded application. Structured design and object-oriented design are the two most popular methodologies. Both of them can be used in embedded systems. However, when a particular language is employed for implementation, we must know the consequence of applying it on a dedicated hardware target. This is especially important for an organization where most of the programmers are familiar with a structured language and have just begun the transition to an object-oriented language. For instance, C is a general-purpose programming language that is relatively compact and efficient. On the other hand, C++ is a "better" C, which supports better data abstraction and object-oriented programming. However, C++ is a far more complex language than C, run-time supports are larger, and run-time costs are often hidden. C++ compiler diagnostics may be difficult to understand and run-time bugs may be subtle. Improper implementations of virtual functions in C++ may increase object size and slow down function calls. Constructors and destructors in C++ (analogous to malloc and free in C) may add overhead to object creation and destruction, and make interrupts and exception handling more complicated. Classes in C++ may have hidden fields that make them difficult to map into existing data structures. Temporary objects in C++ may take unexpected time and space during execution. There could be memory leak problems if no special attention is paid to the memory usage of each programmer or team. Given experienced and properly trained engineers, all these problems may be avoidable.

There is also a wide variety of emerging technologies. Recent references are available from which a reader can learn these technologies and proven theories and learn how to more efficiently implement real-time embedded software. Rate-monotonic scheduling theory is a useful tool that allows system developers to meet the requirements of real-time systems by managing system concurrence and timing

constraints at the tasking and message-passing level [4]. It ensures that all tasks meet their deadlines as long as the system utilization of all tasks lies below a certain bound and appropriate scheduling algorithms are used. System designers can use this theory to predict whether task deadlines will be met, long before the expensive implementation phase of a project begins.

Specification and Description Language (SDL) has been standardized by the International Telecommunication Union (ITU, formerly CCITT) for specifying the behavior of real-time communications systems [5]. The behavior descriptions are based on communicating extended state machines that are represented by processes. An extended state machine consists of a number of states and a number of transitions connecting the states. One of the states is designated the initial state. Communication is represented by signals and can take place between the processes themselves or between the processes and the environment containing the system model. Aspects of communication between processes are closely related to the description of system structure. Probably less known in the ITS field, SDL is widely used in the telecommunications field. SDL is not just for describing telecommunications services. It is a general-purpose description language for communications systems that have complex event-driven, real-time, and interactive applications involving many concurrent activities. Recall that a communications module is a vital component to improve performance and increased functionality of vehicle location and navigation systems as discussed in Chapter 8. SDL could be a very useful development tool for large and complex ITS communications.

Well-structured object-oriented software architectures have numerous patterns. These patterns describe simple and elegant solutions to specific problems in software design. Design patterns capture reusable designs that have developed and evolved over time. Twenty-three very useful design patterns summarized from decades of object-oriented software experience can be found in [6]. For everyday programming, sixty-one short "heuristics" (rules) are presented in [7]. They act as guidelines that can easily be memorized and used in object-oriented design. As mentioned, the object-oriented methodology can be used for embedded real-time system development, but care must be taken when using the C++ programming language because many programmers are migrating from the more familiar C language. Embedded software is tightly connected to its physical environment through various human interventions, sensors, and actuators. It must respond to many events within specified time limits. Interested readers will find additional information on object-oriented methodology and real-time systems in [8], which discusses a variety of detailed design issues and implementation aspects specific to embedded real-time systems when using the C++ programming language.

12.2 FUTURE DIRECTIONS

Some studies suggest that a few standard interfaces should be the top priority for future development of vehicle location and navigation systems. These interfaces

might include an application-layer protocol and a message set for traveler information services, a message standard for mayday systems, and an in-vehicle multiplex bus for ITS devices. A standard ITS data bus interface would allow the vehicle owner to add devices and the manufacturers and dealers to provide new features at much lower cost. Due to the typical design cycles of modern automobiles, it is difficult to install any recently developed electronic device in current-year models. Consumers must take what the vehicle manufacturers offer, or pay more later for an after-market retrofit. A standardized bus would allow easy system integration, so that existing vehicle devices could still be used. It would also allow plug and play with standard modules/connectors on the hardware side and standard application programming interfaces on the software side. It would transform the vehicle into a platform for third-party hardware and software products. It would be much easier to retrofit devices and systems or add new software features and applications. Remote access would be improved, too. It could permit remote diagnosis, upgrades, services, and feature additions. One such concept of an in-vehicle data bus is shown in Figure 12.1 [9].

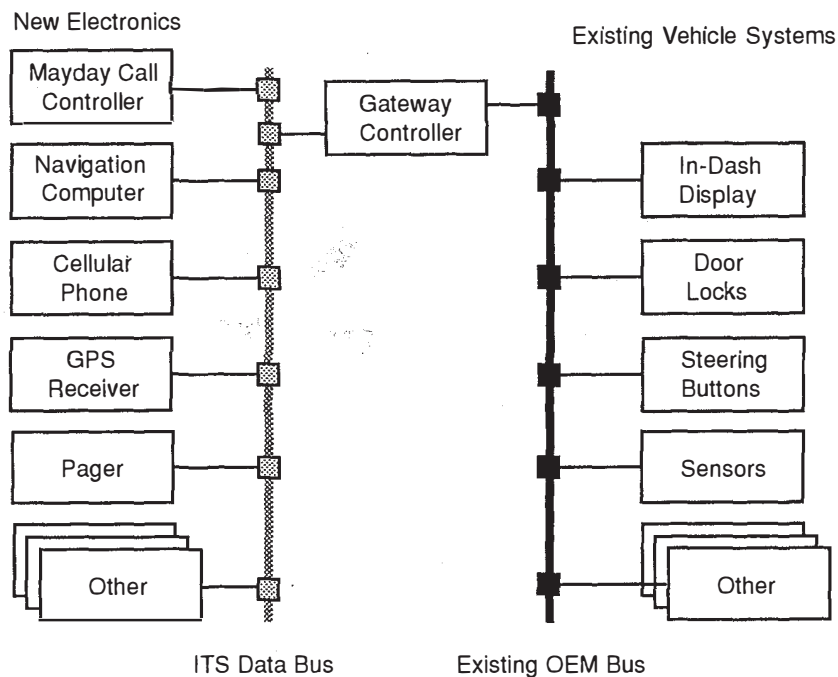


Figure 12.1 Future in-vehicle ITS data bus concept.

Some believe that future vehicles should have more functions to enhance the safety of the driver and vehicle. According to this view, many safety and convenience technologies should be deployed along with the automated highway system (AHS) [10–12]. These technologies include intelligent cruise control (space maintenance, speed control), collision avoidance, vision enhancement, and lane holding (Figure 12.2). Vehicle-to-vehicle communications would further strengthen the support of platooning and the basic roadway infrastructure. Vehicular travel on AHS would be automatically controlled without intervention from drivers or AHS operators. This would provide lanes with higher than normal capacity, in which the space or “headway” between vehicles would be reduced. The vehicles would revert to manual control as they exited the AHS. In addition, electronic (automatic) toll collection plazas and scales might be available along the highway to speed vehicles past toll booths and weigh stations.

Other studies predict that hand-held portable systems will be the navigation systems of the future. Assisted by various infrastructures, these systems would offer many of the same functions as in-vehicle systems [13]. A few early versions of portable systems have already reached the market, with limited functionality. Some use personal digital assistants (PDAs), notebook, or palmtop computers. Others use conventional paging services to provide traffic data. Different approaches exist. For instance, some available systems integrate a portable computer with a GPS receiver mounted on a PCMCIA card in conjunction with digital map and software packages. Some use static databases to provide travel information. In short, more advanced hand-held location and navigation systems will enter the consumer market.

Future automatic vehicle location (AVL) systems will also see many new changes. As wireless communications technologies rapidly advance, various new

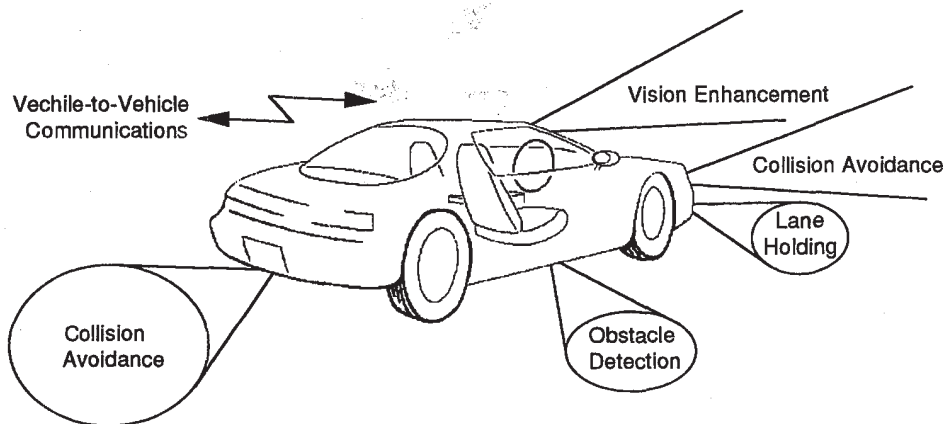


Figure 12.2 Future concept vehicle.

wireless networks may become integrated with AVL systems. In-vehicle terminals may cost less, but still provide many new features. In addition to knowing where they were, law enforcement personnel would be able to access the Internet, WWW pages, or other databases in their vehicles to pull crime files and other information up on the screen in seconds. Many in-vehicle devices could be integrated into a single multifunction device or hand-held device. These new systems may lead to more efficient management of public transit, emergency fleet, hazardous material monitoring, access tracking, and many other public and private systems.

People around the world have similar visions for the future. In Europe, many anticipate the widespread use of the mobile GSM digital cellular phone both for communication and localization, the use of wireless personal travel assistants for intermodal travel, broadcasting of real-time traffic messages via FM radio (RDS-TMC), the development of intelligent cruise control, and a more powerful human-machine interface to display or digest the available information for navigation units. In Japan, people predict more integrated and miniaturized location and navigation systems with a better human-machine interface, much improved voice input devices, increased development and integration of data communications techniques to provide dynamic travel information, and more household media for vehicular use [14]. Navigation systems will become more and more integrated with existing entertainment equipment.

In the United States, mayday systems will continue their successful momentum, although autonomous vehicle navigation systems may eventually catch up as the unit price decreases. Rental cars will initially have the most widespread installed base. As the ITS infrastructure becomes more widely available, centralized navigation systems may gradually dominate the future market because of the benefits of knowing the real-time traffic information. Many autonomous systems might be ready for integration with centralized systems if good system architecture is used in conjunction with newly developed ITS standards. As location and navigation systems evolve, some in-vehicle systems may become more powerful, with additional features such as multimedia, e-mail, fax, and Internet surfing capability. Other systems, such as various mobile (hand-held) devices might become less vehicle dependent. For instance, GPS/cellular, GPS/CDPD, GPS/PDA, and various other technologies (terrestrial radio-based) might soon become available on a much larger scale for hand-held devices. Many of these future mobile devices may be motivated by the FCC's mandatory wireless E911 ruling (Section 10.4). They could be easily carried or plugged into the vehicle and might become either an independent or an integral part of the in-vehicle location and navigation unit while driving. These mobile devices might provide complementary data and exchange data with the in-vehicle navigation systems, home/office information systems, or public computer information terminals at major transport hubs or other information centers. All of these exciting developments will not be restricted to one particular region. In today's global economic environment, they will penetrate rapidly to different regions and eventually the entire

world. As a result, there will be various systems with different services and upgrade capabilities from the very low end to the very high end for everyone to choose from.

Look to the future. The field of vehicle location and navigation is very promising. New and advanced technologies should be able to make transportation operate more safely and efficiently.

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APPENDIX A

TRANSFORMATION BETWEEN CARTESIAN AND ELLIPSOIDAL COORDINATES

We first define the parameters of an ellipsoid as follows:

Semi-major axis: a

Semi-minor axis: b

Flattening: $f = \frac{a - b}{a}$

Eccentricity: $e = \frac{\sqrt{a^2 - b^2}}{a}$, or $= \sqrt{1 - (1 - f)^2}$

Assume that an ellipsoid of revolution is placed at the origin of a Cartesian coordinate system and denote the Cartesian coordinates of a point in space by X, Y, Z and the ellipsoidal coordinates of the same point by ϕ, λ, b . The relationships between the Cartesian coordinates and the ellipsoidal coordinates will then be given by [1,2]

$$X = (N + h)\cos\phi\cos\lambda$$

$$Y = (N + h)\cos\phi\sin\lambda$$

$$Z = \left(\frac{b^2}{a^2}N + h\right)\sin\phi$$

where N is the radius of curvature at the prime vertical which can be obtained by

$$N = \frac{a^2}{\sqrt{a^2\cos^2\phi + b^2\sin^2\phi}}, \text{ or } = \frac{a}{\sqrt{1 - e^2\sin^2\phi}}$$

The inverse transformations are derived as follows [3]:

$$\phi = \arctan \left[\frac{(2t + e^2)z}{(2t - e^2)\sqrt{x^2 + y^2}} \right]$$

$$\lambda = 2\arctan \left[\frac{\sqrt{x^2 + y^2} - x}{y} \right]$$

$$h = \text{sign} \left(t + \frac{e^2}{2} - 1 \right) \sqrt{(x^2 + y^2) \left(1 - \frac{2}{2t + e^2} \right)^2 + z^2 \left(1 - \frac{2(1 - e^2)}{2t - e^2} \right)^2}$$

where

$$t = \sqrt{\sqrt{\beta^2 - k} - \frac{(\beta + i)}{2}} - \text{sign}(m - n) \sqrt{\frac{(\beta - i)}{2}}$$

$$\beta = \frac{i}{3} - \sqrt[3]{q + D} - \sqrt[3]{q - D}$$

$$k = \frac{e^4}{4} \left(\frac{e^4}{4} - m - n \right)$$

$$i = -\frac{\left(\frac{e^4}{2} + m + n \right)}{2}$$

$$m = \frac{x^2 + y^2}{a^2}$$

$$n = \left[\frac{(1 - e^2)z}{b} \right]^2$$

$$q = \frac{(m + n - e^4)^3}{216} + \frac{mne^4}{4}$$

$$D = \sqrt{\left(2q - mn\frac{e^4}{4}\right)mn\frac{e^4}{4}}$$

Note that when $\sqrt{x^2 + y^2} = 0$

$$h = \text{sign}(z)z - b$$

$$\phi = \text{sign}(z)\frac{\pi}{2}$$

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APPENDIX B

TRANSFORMATION BETWEEN UTM AND ELLIPSOIDAL COORDINATES

In the Universal Transverse Mercator (UTM) projection, based on the same ellipsoidal parameters defined in Appendix A, the transformation equations for transforming an ellipsoidal point (ϕ, λ) to a point (y, x) on the UTM plane are given by the following series expansions [1,2]:

$$\begin{aligned}
 y &= kS(\phi) + kN \left[\frac{t}{2} \cos^2 \phi (\lambda - \lambda_0)^2 + \frac{t}{24} \cos^4 \phi (5 - t^2 + 9\eta^2 + 4\eta^4)(\lambda - \lambda_0)^4 \right. \\
 &\quad + \frac{t}{720} \cos^6 \phi (61 - 58t^2 + t^4 + 270\eta^2 - 330t^2\eta^2)(\lambda - \lambda_0)^6 \\
 &\quad \left. + \frac{t}{40320} \cos^8 \phi (1385 - 3111t^2 + 543t^4 - t^6)(\lambda - \lambda_0)^8 + \dots \right] \\
 x &= kN \left[\cos \phi (\lambda - \lambda_0) + \frac{1}{6} N \cos^3 \phi (1 - t^2 + \eta^2)(\lambda - \lambda_0)^3 \right. \\
 &\quad + \frac{1}{120} \cos^5 \phi (5 - 18t^2 + t^4 + 14\eta^2 - 58t^2\eta^2)(\lambda - \lambda_0)^5 \\
 &\quad \left. + \frac{1}{5040} \cos^7 \phi (61 - 479t^2 + 179t^4 - t^6)(\lambda - \lambda_0)^7 + \dots \right]
 \end{aligned}$$

where

Arc length of meridian:	$S(\phi)$
Radius of curvature in prime vertical:	$N = \frac{a^2}{b\sqrt{1 + \eta^2}}$
Auxiliary quantity:	$\eta^2 = e'^2 \cos^2 \phi$
Second numerical eccentricity:	$e'^2 = \frac{a^2 - b^2}{b^2}$
Auxiliary quantity:	$t = \tan \phi$
Longitude of the central meridian:	λ_0
UTM scale factor:	$k = 0.9996$

Because the pair of coordinates (y, x) corresponds to (ϕ, λ) , y is given first followed by x . The arc length of the meridian $S(\phi)$ is the ellipsoidal distance from the equator to the point to be transformed and is given by the series expansion

$$S(\phi) = \alpha[\phi + \beta \sin 2\phi + \gamma \sin 4\phi + \delta \sin 6\phi + \epsilon \sin 8\phi + \dots]$$

where

$$\alpha = \frac{a+b}{2} \left(1 + \frac{1}{4}n^2 + \frac{1}{64}n^4 + \dots \right)$$

$$\beta = -\frac{3}{2}n + \frac{9}{13}n^3 - \frac{2}{32}n^5 + \dots$$

$$\gamma = \frac{15}{16}n - \frac{15}{32}n^4 + \dots$$

$$\delta = -\frac{35}{48}n^3 + \frac{105}{256}n^5 - \dots$$

$$\epsilon = \frac{315}{512}n^4 + \dots$$

$$n = \frac{a-b}{a+b}$$

As an example, the parameters of the WGS 84 reference ellipsoid (Table 2.1) are listed here:

$$\begin{aligned}\alpha &= 6367449.1458\text{m} \\ \beta &= -2.51882792 \times 10^{-3} \\ \gamma &= 2.64354 \times 10^{-6} \\ \delta &= -3.45 \times 10^{-9} \\ \epsilon &= 5 \times 10^{-12} \\ n &= 1.67922 \times 10^{-3}\end{aligned}$$

The inverse UTM projection is the transformation of a point y, x in the plane to a point ϕ, λ on the ellipsoid. The transformation equations are given by the following series expansions:

$$\begin{aligned}\phi &= \phi_f - \frac{t_f}{2}(1 + \eta_f^2)\left(\frac{x}{kN_f}\right)^2 \\ &\quad + \frac{t_f}{24}(5 + 3t_f^2 + 6\eta_f^2 - 6t_f^2\eta_f^2 - 3\eta_f^4 - 9t_f^2\eta_f^4)\left(\frac{x}{kN_f}\right)^4 \\ &\quad - \frac{t_f}{720}(61 + 90t_f^2 + 45t_f^4 + 107\eta_f^2 - 162t_f^2\eta_f^2 - 45t_f^4\eta_f^2)\left(\frac{x}{kN_f}\right)^6 \\ &\quad + \frac{t_f}{40320}(1385 + 3633t_f^2 + 4095t_f^4 + t_f^6)\left(\frac{x}{kN_f}\right)^8 + \dots \\ \lambda &= \lambda_0 + \frac{1}{\cos\phi_f}\left(\frac{x}{kN_f}\right) - \frac{1}{6\cos\phi_f}(1 + 2t_f^2 + \eta_f^2)\left(\frac{x}{kN_f}\right)^3 \\ &\quad + \frac{1}{120\cos\phi_f}(5 + 28t_f^2 + 24t_f^4 + 6\eta_f^2 + 8t_f^2\eta_f^2)\left(\frac{x}{kN_f}\right)^5 \\ &\quad - \frac{1}{5401\cos\phi_f}(61 + 662t_f^2 + 1320t_f^4 + 720t_f^6)\left(\frac{x}{kN_f}\right)^7 + \dots\end{aligned}$$

where the terms with the subscript f must be computed based on the footpoint latitude ϕ_f . The series expansion of the footpoint latitude is given by

$$\phi_f = \frac{y}{k\bar{\alpha}} + \bar{\beta}\sin 2\frac{y}{k\bar{\alpha}} + \bar{\gamma}\sin 4\frac{y}{k\bar{\alpha}} + \bar{\delta}\sin 6\frac{y}{k\bar{\alpha}} + \bar{\epsilon}\sin 8\frac{y}{k\bar{\alpha}} + \dots$$

where

$$\bar{\alpha} = \frac{a+b}{2} \left(1 + \frac{1}{4}n^2 + \frac{1}{64}n^4 + \dots \right)$$

$$\bar{\beta} = \frac{3}{2}n - \frac{27}{32}n^3 + \frac{269}{512}n^5 + \dots$$

$$\bar{\gamma} = \frac{21}{16}n^2 - \frac{55}{32}n^4 + \dots$$

$$\bar{\delta} = \frac{151}{96}n^3 - \frac{417}{128}n^5 + \dots$$

$$\bar{\epsilon} = \frac{1097}{512}n^4 + \dots$$

Note that the coefficient $\bar{\alpha}$ is identical to α in the previous transformation. As an example, the parameters for the WGS 84 reference ellipsoid are listed:

$$\bar{\alpha} = 6367449.1458 \text{ m}$$

$$\bar{\beta} = 2.51882658 \times 10^{-3}$$

$$\bar{\gamma} = 3.70095 \times 10^{-6}$$

$$\bar{\delta} = 7.45 \times 10^{-9}$$

$$\bar{\epsilon} = 17 \times 10^{-12}$$

Note that for location and navigation applications, the higher order terms indicated by ellipses can be ignored. Setting the UTM scale factor equal to one leads to the transformation equations for the transverse Mercator projection.

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APPENDIX C



POSITIONING SENSOR TECHNOLOGIES

To become familiar with the sensor technologies used to determine position, we have summarized the families and underlying principles of various types of linear and angular vehicular position sensors in Tables C.1 and C.2, respectively. Some sensors listed can be used for velocity measurement. Note that the boundaries of some sensor families are vague because they may have hybrid elements produced by mechanical, electrical, or other technologies. The tables attempt to illustrate the variety of technologies available. Because of rapid progress in sensor technologies, it is very difficult to cover them all in two tables. Many technologies can be used for either linear sensors or angular sensors. Certain technologies may not be suitable for vehicle positioning applications at the moment.

Table C.1
Linear Position Sensors

<i>Family</i>	<i>Sensor</i>	<i>Underlying Principle</i>
Mechanical	Microswitch	Simple on and off
	Reed switch	Activated when aligned with magnetic flux
Electromechanical	Eddy current	Currents induced in conductive object
	Hall effect	Voltage across semiconductor in magnetic field
	Linear variable differential transformer (LVDT)	Coupled transformers with moving core
	Magnetic transistor	Voltage across transistor in magnetic field
Electro-optical	Variable reluctance	Changes in reluctance within magnetic circuit
	Wiegand effect	Voltages induced by magnetic pulses
	Charge-coupled device (CCD) array, lateral effect photodiodes	Charge is proportional to incident light
	Laser	Time required to transmit and receive laser energy
	Light curtain	Through-beam array of source detector pairs
Solid state	Linear optical encoder	Source/detector pair interrupted by slits
	Interferometer	Optical phase
	Radar (microwave)	Time required to transmit and receive
	Magnetoresistive element	Resistance change in proportion to magnetic field strength
Acoustic	Ultrasonic	Time required to transmit and receive piezoelectric transducer pulses or Doppler effect

APPENDIX D



LEAST SQUARES ALGORITHM

Given the following equation:

$$Y = AX$$

where Y is the known $n \times 1$ vector of measurements, X is the $m \times 1$ vector of unknowns, and A is the $n \times m$ design matrix.

If $n > m$, the system has more equations than unknowns. The method of least squares can be used to obtain an optimal estimate for X using the redundant set of measurements.

Let us define the $n \times 1$ vector of residuals as follows:

$$r = AX - Y$$

We now need to find the value for X that minimizes the sum squares of the residuals, that is,

$$f(X) = (AX - Y)^2 = (AX - Y)^T(AX - Y)$$

where T indicates the transpose operation. Differentiating the preceding equation and setting the result to zero, we obtain

$$\frac{df(\mathbf{X})}{d\mathbf{X}} = 2\mathbf{A}^T\mathbf{A}\mathbf{X} - 2\mathbf{A}^T\mathbf{Y} = 0$$

Provided $\mathbf{A}^T\mathbf{A}$ is nonsingular, we solve for $\mathbf{X}$ and obtain

$$\mathbf{X} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{Y}$$

This is the least squares solution, where $(\mathbf{A}^T\mathbf{A})^{-1}$ is the cofactor matrix we studied in Section 3.3. If $n = m$ and $\mathbf{A}$ is nonsingular, the least squares solution reduces to the following unique solution:

$$\mathbf{X} = \mathbf{A}^{-1}\mathbf{Y}$$

Note that the observations can be weighted based on the accuracy of each observation. The preceding solutions describe the equal-weight case. For more information, refer to [1,2].

References

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APPENDIX E



KALMAN FILTER ALGORITHM

The optimum combination of measured and estimated results at time t_k is given by

$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k^- + \mathbf{K}_k(\mathbf{z}_k - \mathbf{H}_k\hat{\mathbf{x}}_k^-)$$

where $\hat{\mathbf{x}}_k^-$ denotes the a priori estimate. The “hat” denotes estimate and the superscript minus indicates that this is our best estimate prior to assimilating the measurement at time t_k .

The Kalman filter gain used in the equation just given can be written as

$$\mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}_k^T (\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T + \mathbf{R}_k)^{-1}$$

and the error covariance matrix associated with the optimal estimate is obtained from

$$\mathbf{P}_k = (\mathbf{I} - \mathbf{K}_k \mathbf{H}_k) \mathbf{P}_k^-$$

To recursively compute the Kalman filter gain for the next step, the predictions for the state estimate and covariance at the next step are given by

$$\begin{aligned}\hat{\mathbf{x}}_{k+1}^- &= \phi_k \hat{\mathbf{x}}_k \\ \mathbf{P}_{k+1}^- &= \phi_k \mathbf{P}_k \phi_k^T + \mathbf{Q}_k\end{aligned}$$

In these equations the covariance matrices $\mathbf{Q}_k$ and $\mathbf{R}_k$ are obtained from the $\mathbf{w}_k$ (process noise) and $\mathbf{v}_k$ (measurement noise) vectors as follows:

$$\begin{aligned}E[\mathbf{w}_k \mathbf{w}_i^T] &= \begin{cases} \mathbf{Q}_k, & i = k \\ 0, & i \neq k \end{cases} \\ E[\mathbf{v}_k \mathbf{v}_i^T] &= \begin{cases} \mathbf{R}_k, & i = k \\ 0, & i \neq k \end{cases} \\ E[\mathbf{w}_k \mathbf{v}_i^T] &= 0, \text{ for all } k \text{ and } i\end{aligned}$$

and, for the error covariance matrix $\mathbf{P}_k$,

$$\mathbf{P}_k^- = E[(\mathbf{x}_k - \hat{\mathbf{x}}_k^-)(\mathbf{x}_k - \hat{\mathbf{x}}_k^-)^T]$$

To derive the preceding estimation equations, we assume that the random process to be estimated can be modeled in the form

$$\mathbf{x}_{k+1} = \phi_k \mathbf{x}_k + \mathbf{w}_k$$

and the measurement (observation) of the process can be modeled as

$$\mathbf{z}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{v}_k$$

Detailed discussions of this algorithm can be found in [1-4].

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APPENDIX F



FUZZY LOGIC BACKGROUND

Fuzzy set theory, introduced by Zadeh [1] in 1965, has been shown to be an effective way to deal with qualitatively oriented terms and concepts. Fuzzy logic provides a simple way to draw definite conclusions from vague, imprecise information. In an intuitive sense, it resembles human decision making. For example, consider the following declarative assertion concerning a vehicle traveling on a local residential road:

“The speed of this vehicle is high.”

If the speed is 100 km/h, this statement is completely true. However, if 100 km/h is high, how about 99, 98, ... 90, ... 80, ... 70? At what degree does the statement suddenly become false? Since the speed can change gradually during a trip, it is hard to find a fixed value such that larger than that fixed value is “high” and less than that value is “not high.” To resolve this fuzziness, we can assign a grade, or membership degree, to a speed. A speed is high only to a certain degree of truth, called a grade, or membership degree. By correlating various speeds to grades, we turn the preceding statement into a fuzzy membership function. Therefore, people often say that fuzzy logic is a mathematical formalism intended to handle these kinds of imprecise statements. It is different from traditional mathematical formalisms because fuzzy logic allows us to model the vagueness in our mental decision-making process. Consequently, fuzzy logic is intuitive and easier to work with than traditional

logic for many applications. Traditional logic would have a difficult time processing the given statement. In the design of fuzzy inference systems, there are three basic concepts: membership functions, fuzzy logic operations, and fuzzy rules.

For membership functions, we can denote the grade of a speed in high by assigning it a numerical "truth value." Truth values may range anywhere between 0 and 1 and are typically considered to have meaning as suggested in Table F.1, although it may not always have meaning. In this manner we can arbitrarily assign various grades to "high" as a function of the speed (Table F.2).

The membership functions given in the tables are illustrated in Figure F.1. The curve in the figure illustrates how the membership function of a fuzzy concept is dependent on a measured value, for example, speed. When the relevant declarative assertions are combined into a single chart, more complicated curves are obtained. These curves are called fuzzy sets. The fuzzy concept "high" is called a label. For a speed, such as 70 km/h, 0.7 is its grade in high. In other words, if the speed of this

Table F.1
Linguistic Meanings of Fuzzy Logic Values

<i>Truth Value</i>	<i>Meaning</i>
0.0	Completely false
0.2	Mostly false
0.4	Somewhat false
0.6	Somewhat true
0.8	Mostly true
1.0	Completely true

Table F.2
Membership Function

<i>Speed (km/h)</i>	<i>Grade in High</i>
0	0.0
10	0.1
20	0.2
30	0.3
40	0.4
50	0.5
60	0.6
70	0.7
80	0.8
90	0.9
100	1.0

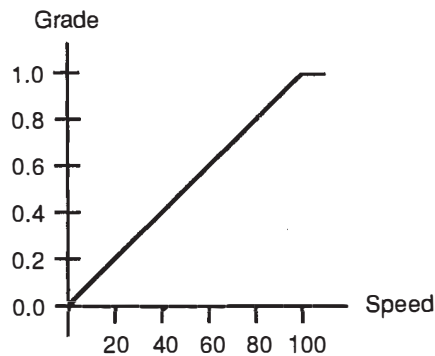


Figure F.1 Membership function chart.

vehicle is 70 km/h, the truth value of the assertion "The speed of this vehicle is high" is 0.7.

For fuzzy logic operations, consider our spoken language. In addition to the simple assertion statement presented earlier, logical operators are often used in spoken language to combine simple assertions into more complex ones. Examples of such operators are "AND" and "OR." Assertions using these operators are called compound assertions. Similar operators can be used in fuzzy logic to help evaluate the truth values of these assertions. These operations are called fuzzy logic operations. For example, let us define another simple assertion:

"The distance to the next maneuver is short."

We can now create a compound assertion:

"The speed of this vehicle is high AND the distance to the next maneuver is short."

Once a truth value is assigned to each simple assertion, fuzzy logic operations can precisely evaluate the truth values of compound assertions. Even though the compound assertion is vague, the evaluation results are crisp values. In other words, nothing is fuzzy in the actual fuzzy inference process.

As examples, let us examine how to evaluate truth values for statements containing the two simple operators, AND or OR. Mathematical functions are used by fuzzy logic to evaluate two arbitrary statements A and B. These statements can be either simple or compound. The mathematical functions are listed in the right-hand column of Table F.3. Each of them is associated with its corresponding fuzzy logic operator in the left-hand column.

From the definitions given in Table F.3, we can easily evaluate the truth value of any statement. Let the truth value of A be 0.1 and that of B be 0.8. We obtain

Table F.3
Fuzzy Logic Operations

<i>Compound Operator on Statements A, B</i>	<i>Mathematical Function to Evaluate Truth</i>
A AND B	minimum (min)
A OR B	maximum (max)

Assertion 1: $A \text{ AND } B = \min(0.1, 0.8) = 0.1$

Assertion 2: $A \text{ OR } B = \max(0.1, 0.8) = 0.8$

The crisp truth value of Assertion 1 is 0.1, whereas Assertion 2 has a value of 0.8.

We now know that a traditional logic such as Boolean logic is a special case of fuzzy logic. If you doubt this statement, see Table F.4, which lists various evaluation results for two compound assertions. Both results obtained by applying fuzzy logic operators and Boolean logic operators are derived. Note that both fuzzy logic and Boolean logic produce the same results when the truth values of the simple assertions are limited to 1 and 0. However, for values other than 1 or 0, fuzzy logic produces meaningful results while Boolean logic has no such operations defined.

For fuzzy rules, consider the following example. Suppose that we want to determine when to announce a maneuvering instruction via a speaker to a driver during route guidance. One of rules could be

IF the speed of this vehicle is high AND the distance to the next maneuver is short

THEN announce the next maneuver instruction.

Table F.4
Comparison of Boolean Logic and Fuzzy Logic Operations

<i>Logic Operator</i>		<i>Fuzzy Logic</i>		<i>Boolean Logic</i>	
A	B	A AND B	A OR B	A AND B	A OR B
0	0	0	0	0	0
0	1	0	1	0	1
1	0	0	1	0	1
1	1	1	1	1	1
0	0.6	0	0.6	?	?
0.5	0.5	0.5	0.5	?	?
0.8	0.6	0.6	0.8	?	?
1	0.6	0.6	1	?	?

In other words, a rule has the following format:

IF <condition> THEN <consequence>.

The condition part of a rule could be either a simple or compound statement and the consequence part is typically a simple statement. The input to a fuzzy-logic-based system is very similar to human language. The more complex a system is, the more rules it will generally have. Given the input grades in the condition part, each rule is evaluated to obtain an output grade in the consequence part.

The final result of this inference process depends on the combinational effect of many fuzzy rules in the process. Because a single number is desired as output, we need a defuzzifying operation. In other words, a defuzzification operator is used to compute one final crisp output value, which is to make a decision for the system to follow. We can view this final step as interpreting the evaluated grades as a measure of confidence in the corresponding conclusion. The most popular method used for this operation is to compute the centroid (weighted average) of the output from the fuzzy rules. By considering the grades as weights attached to the assertions, the final decision z is obtained by determining the weighted average of the support values associated with each output label:

$$z = \frac{\sum_{i=1}^n x_i y_i}{\sum_{i=1}^n y_i}$$

where x is the position of the fuzzy output from the evaluation, y is the value (weight) of the corresponding fuzzy output, and n is the number of fuzzy outputs. In general, the outputs of fuzzy rule evaluation results are discrete values. For convenience, a curve is used in Figure F.2 to explain the basic concept.

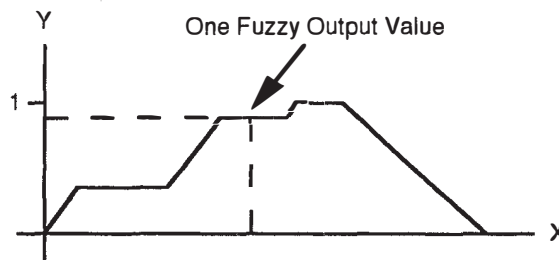


Figure F.2 Example of a fuzzy output curve.

To summarize, the fuzzy logic inference process consists of the following three steps:

1. Fuzzification;
2. Rule evaluation;
3. Defuzzification.

As discussed before, fuzzification converts the input values into grades (fuzzy values) using input labels. This is often called relating crisp values to fuzzy sets by the membership functions of input labels. The rule evaluation step computes the grade of each output label, that is, the fuzzy output truth values are computed in this step. In general, this step involves rather complicated operations. It uses a inference engine with the membership functions of fuzzy sets to perform fuzzy reasoning on the rules. Defuzzification involves interpreting these grades as a measure of the confidence in the corresponding conclusions. It makes the final decision for the whole inference process. In other words, it converts the outcome of the fuzzy reasoning process into a crisp value that can be used to control the system or it can merely be presented to the system.

Different fuzzy logic operators are used for processing and interpreting rules and different defuzzification operators are used for deriving the final decision. In addition to AND (minimum) and OR (maximum), other examples of logic operators include product, probability sum, bounded intersection, bounded union, etc. Examples of defuzzification operators are centroid, leftmost maximizer, rightmost maximizer, average maximizer, etc. Details on the operators and fuzzy inference methods that are available can be found in [2,3].

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