Outline of the Comprehensive Automobile Traffic Control Pilot Test System

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In the final phase of the Comprehensive Automobile Traffic Control Project, a pilot system was constructed and put into operation in October 1977. In the pilot area, which covers 28 km^2 in southwestern Tokyo, a two-way exchange of digital information occurs between instrumented vehicles and roadside equipment. The driver receives a visual display of routing information that is based on current traffic conditions and other information for safe driving. In order to provide the drivers of noninstrumented vehicles with the routing information, new roadside displays were developed. A roadside radio system, which gives the driver traffic information and provides instructions in an emergency, was also developed. This paper presents an overview of the pilot system and describes the procedure of optimum route finding, the specification of the digital communication link between road and vehicle, and the hardware features of the principal equipment. A preliminary evaluation of the system performance is also described.

The Comprehensive Automobile Traffic Control (CAC) Project (1, 2), sponsored by the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry, was begun in 1973 for a six-year research period with a budget of seven billion yen [¥ 220 = $1.00 (August 1979)].

The objective of this project is to develop an integrated system that provides, by means of an improved communication medium between vehicles and the external world, such functions as optimum route guidance, diversion of traffic out of high-density pollution areas, priority for public service vehicles, advanced display of traffic regulations and alerts, and the potential for simultaneous communication in case of emergency. Such a system will contribute to an improved public acceptance of automobile transportation by reducing traffic congestion, traffic accidents, and air pollution.

The principal technical activities undertaken to achieve this objective were to develop (a) an optimum control strategy of traffic flow, as well as monitoring of vehicular movement and assignment of optimum route; (b) a high-speed and reliable two-way communication system between the individual vehicle and the ground; and (c) an excellent display method that considers human engineering factors. In 1974, prototype hardware was developed and evaluated in a preliminary experimental installation within the grounds of a factory.

Between 1975 and 1976, the software and hardware for the pilot system were manufactured and installed in a 28-km^2 test area in the southwestern part of Tokyo. The purposes of the pilot test include evaluating the effectiveness of the system in an actual urban situation, identifying potential problems regarding future adoption of the system, demonstrating the system to the public, and obtaining their opinions about it. The pilot system has been in actual operation since October 1977.

OUTLINE OF THE PILOT SYSTEM

Communication Between the Driver and the System

The pilot system has three means of communication between the driver and the ground:

1. Two-way digital communication link by inductive radio (when the vehicle's antenna passes over the road antenna, a data transmission of about 100 bits in each direction occurs via the magnetic field between both antennas),
2. Ground-to-vehicle oral communication by means of a roadside radio (radio transmission reaches only the vehicles that pass the roadside antenna, which extends along the street), and
3. Roadside visual display.

Functions of the Pilot System

The pilot system has five subfunctions:

1. Route guidance, which gives the driver a visual instruction at decision points and guides the driver to his or her destination in the same way that the Experimental Route Guidance System (ERGS) does (3) [the CAC system differs from ERGS in that the route is periodically optimized on the basis of the current traffic and road conditions and in that the system has functions other than route guidance];
2. Driving information, which gives the driver a visual display of information useful for safe driving and gives him or her a sonic alert when the vehicle exceeds the speed limit according to ground control;
3. Priority for public service vehicles, which gives priority to public service vehicles at the signalized intersections and improves the operating efficiency of such vehicles by continuous monitoring of their individual locations;
4. Urgent information, which gives the driver instructions in an emergency and provides audio information on localized traffic and road conditions in usual situations; and
5. Roadside route display, which gives drivers of noninstrumented vehicles the routing information.

The route guidance, driving information, and priority for public service vehicles subsystems use the digital communication link by inductive radio. The vehicle type, its identification number, and destination code are sent from the vehicle to the ground. Routing and driving information are sent in the opposite direction. At some locations where only driving information is necessary, downward data are neglected by the ground.

The urgent information subsystem uses the roadside radio. The audio medium of communication supplements the visual display of route guidance and driving information and provides the driver with more versatile information than digital communication does.

Configuration of the Pilot System

Arterial streets and expressways of about 100 km in total length within an area surrounded by Loop Road No. 7 and the national highways Route 1 and Route 246 were chosen as the test site.

Figure 1 shows the layout of the pilot test area. At 74 intersections on the arteries and 15 forks on the expressways, instrumented vehicles exchange digital data with roadside equipment for the route guidance and driving information subsystems. In addition, 15 locations are equipped with roadside equipment exclusively for the driving information subsystem. At 9 locations, 400-m-long leaky coaxial cables are installed as roadside radio antennas. Along an artery bound for the central business district, three roadside displays are installed.

The roadside equipment for the route guidance and driving information subsystems is connected via leased, duplex 1200-band lines to a communication control computer located at the control center. Routing information and driving information are sent from the center to the roadside equipment, and the data received from the vehicles are sent in the opposite direction. About 180 vehicle detectors are installed, 40 of which are connected to the communication control computer through leased 50-band lines and a central preprocessor; 130 others are connected to the roadside equipment, preprocessed, and then sent to the center with other information.

The data from the communication control computer are fed to the main computer, which estimates travel time along each link of the road network, based on the time of data exchange with each vehicle at each communication point and on the traffic volume and occupancy, measured by means of vehicle detectors. The main computer keeps a data base on the road network and interfaces with the operators through an operation control computer.

The main computer sends the travel time data to a pair of minicomputers or to a traffic network simulator that finds minimum travel-time routes and generates guide tables. The guide tables are sent to the roadside equipment through the communication control computer.

The contents of the roadside route display subsystem and the messages of the urgent information subsystem are manually controlled. The main computer makes suggestions about the contents and messages based on the data it keeps. The contents of the roadside route display subsystem are monitored at the traffic control center of the Metropolitan Police Department. An agreement between the CAC system operator and the police officer on duty is necessary to effect the display.

In-vehicle units for route guidance and driving information are mounted in 330 vehicles, 290 of which are owned by voluntary participants in the test. The remaining 40 are operated exclusively as research vehicles; these are also equipped with urgent information subsystem radio receivers. In order to obtain travel-time measurements, an additional 1000 vehicles are equipped with in-vehicle units that do not have display capability.

The pilot system was recently expanded to include a stretch of expressways between the new Tokyo International Airport in Narita and the City Air Terminal in downtown Tokyo (Figure 2). At seven places along the road, roadside equipment was installed and connected to a line concentrator and a minicomputer in Chiba Operations Center of the Japan Highway Public Corporation. Transceivers were installed on about 70 limousines that commute nonstop between the airport and the City Air Terminal. By means of these installations, travel time between each point is obtained about every 15 min. The information is transferred to the CAC system center via a leased line to monitor and analyze the data.

DISPLAY INSIDE VEHICLES

Figure 3 provides a conceptual schematic drawing of the route guidance and driving information subsystems (4). Figure 4 shows the inside view of an instrumented vehicle. The driver enters a seven-digit destination code into the encoder, informing the system of any option regarding expressway use by pressing the "expressway option" button. The expressway option, as well as the type of the vehicle, is taken into account in route selection.

The data received at a communication point are stored on board the vehicle and displayed step by step as shown in Figure 5. First, the display indicates the entrance lane to take before entering the intersection and the direction of turning movement at that intersection. Second, by keeping the indication of the turning direction, the display indicates the exit lane to take after departing from the intersection. This is intended to ease the maneuver at the next intersection. Third, the entrance lane and the turning direction to be taken at the next intersection are indicated, if necessary. The distance between the communication point and the places where the indications should be changed are controlled by data from the ground. A chime sounds when the indication changes.

The turning direction is indicated superimposed over the shape of the intersection (up to seven shapes exist). After departing from a route guidance intersection, a "go straight" indication is held until the vehicle approaches the next one. The final indication of the turning direction flashes when the vehicle approaches the destination. An up or down indication at a grade separation, entrance or exit indication at an expressway ramp, and indications of detour, impossibility of guidance, and transmission error are also displayed.

The driving information subsystem consists of warning information and speed-limit violation alert. The warning information is indicated in characters. The appropriate instructions from the following six are selected and displayed for about 10 s: (a) pedestrian crossing, (b) reduce speed, (c) changing road width, (d) stop and go, (e) priority lane, and (f) road work ahead.

An "alert" sound warns the driver when the speed of his or her vehicle exceeds the speed limit, according to the ground control.

ROUTING CALCULATION

Structure of Road Network Model

Each of the inbound and outbound links between adjacent route guidance intersections is called a point. A unique seven-digit destination code is given to each point (see Figure 6). Paths connecting adjacent points are called arcs. An arc is directional.

The whole Japanese road network is divided into about 100 regions as shown in Figure 7. Each region is subdivided into as many as 63 sections. Each section is subdivided into as many as eight zones. Each zone contains up to 63 points.

The pilot test area consists of five sections and contains 330 points and 680 arcs.

Approximation of Network Model

In order to reduce the computational load without an adverse effect on the quality of route selection, the network is approximated in a way that is accurate near the origin and becomes more simplified going away from the origin.

As shown in Figure 8, in an area composed of the section to which the origin belongs and the sections that circumscribe the origin section, the network is not approximated. We shall call this area the nonsimplified area.

Figure 1. Pilot test area.

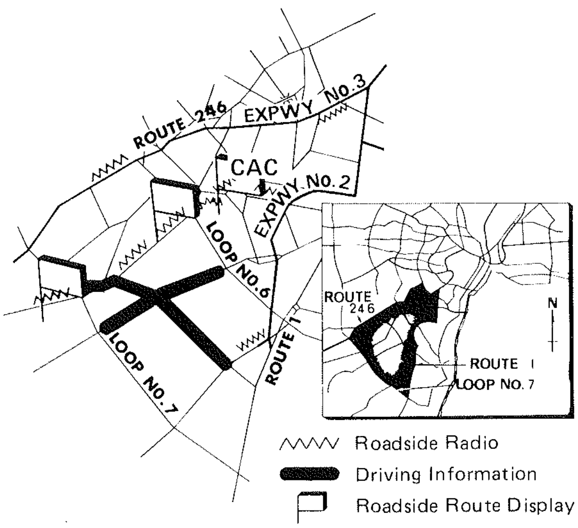
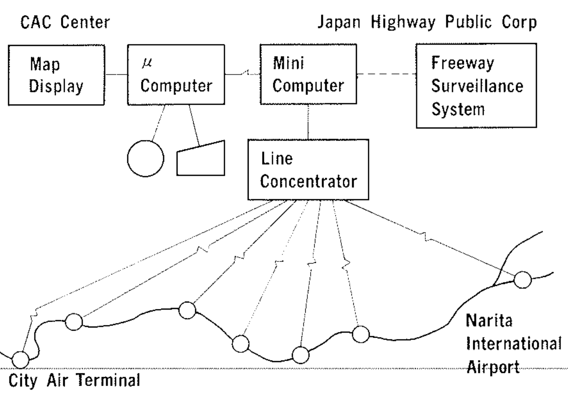


Figure 2. Travel time measurement between Narita Airport and City Air Terminal.



In the sections that circumscribe the nonsimplified area, structure of the network within a zone is neglected, and a zone is treated as a point and represented by a representative point in it. A representative point is tied to the neighboring representative points and to the border of the nonsimplified area by hypothetical arcs called regenerated arcs. Remaining sections in and regions outside the origin region are treated as points. The travel time along a regenerated arc between zones is determined by calculation of the travel time along the optimum route on the actual network.

Route Calculation

Travel time to a certain point from the origin point along the route is defined as the route travel time of the point. Branches are extended from the origin point to all of the succeeding points. From those points, branches are further extended successively. When two arcs run into the same point, the arc that gives the smaller route travel time is included in the route and the other arc is excluded from the route. The above procedure is repeated until all the points are reached.

Since certain arcs inhibit the types of vehicles that may pass, the optimum route depends on the vehicle type. Taking into consideration that the route from the origin to the inhibited arc is common to both vehicle types, the route calculation is carried out only for the portion of the network beyond the inhibited arc.

This principle is also applied to treatment of the expressway option, because avoidance of an expressway can be considered to block the arc entering an expressway.

The pilot test system has two alternative means of route calculation: a software mode with a pair of minicomputers and a hardware mode with a traffic network simulator.

Guide Table

As a result of the routing calculation, a list of routing information for each destination is obtained for each intersection. The routing information is a series of exit links, each of which corresponds to a certain combination of the entrance link, expressway option, and vehicle type.

In respect to the routing information, destination codes are grouped and arranged into a tree structure called the destination table, in which the hierarchy of code corresponds to the structure of the tree. The terminal branch of the tree points entries to the entrance link table, which in turn points to the vehicle-type table.

Figure 3. Schematic drawing of route guidance and driving information subsystems.

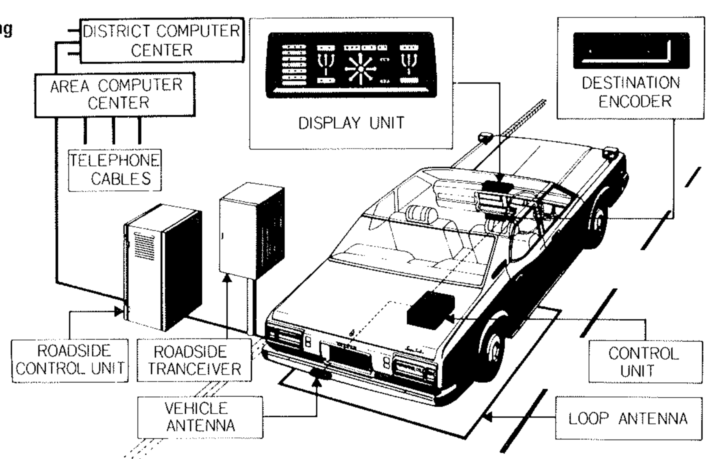


Figure 4. Display and encoder in the vehicle.

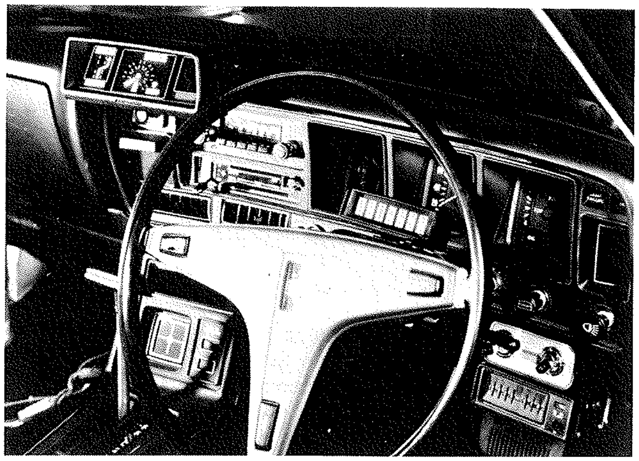
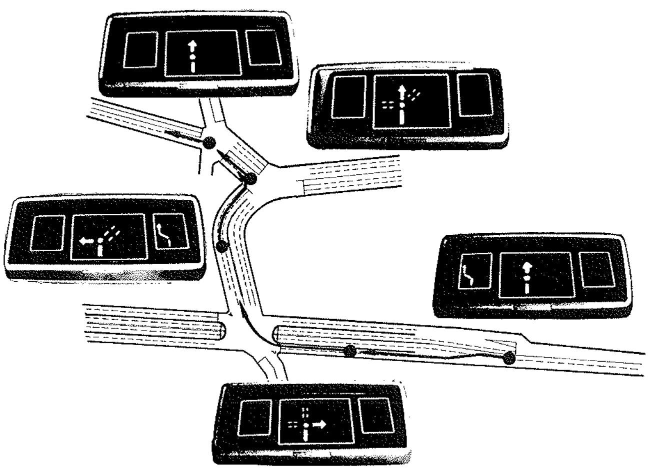


Figure 5. Display of routing instructions.



When the routing information differs by expressway option, the entrance link table is indirectly pointed via an expressway ramp table. A guide table, composed of the destination table, the expressway ramp table, the entrance link table, and the vehicle-type table, is generated for each intersection and sent to the roadside equipment (Figure 9).

DIGITAL COMMUNICATION BETWEEN VEHICLE AND GROUND

The vehicle transmits to the ground the request data, which consist of a 28-bit destination code, 1-bit expressway option, 31-bit vehicle identification number, and 8-bit vehicle-type code. In response, the ground sends a 58-bit route guidance message and a 12-bit driving message. The length of the message in each direction is 81 bits, including dummy and parity check bits (Figure 10).

The message is encoded into a modified NRZ code, which modulates the phase of the carrier. The carrier frequency is 172.8 kHz for vehicle to ground and 105.6 kHz for ground to vehicle. The transmission speed is 4800 bits/s. A parity check bit is inserted every 8 data bits.

The ground antenna is a 1-turn loop 2.5 m wide and 3 m long. The vehicle antenna is a 30-turn loop of 100x50 mm that is attached under the rear bumper to

Figure 6. Road network model.

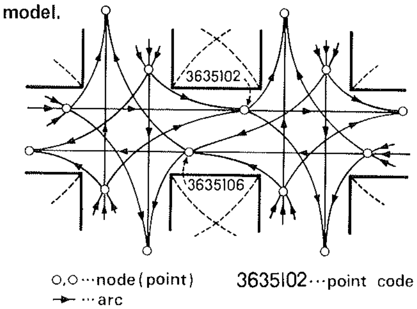


Figure 7. Nationwide region code.

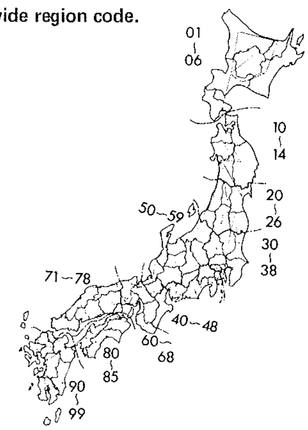
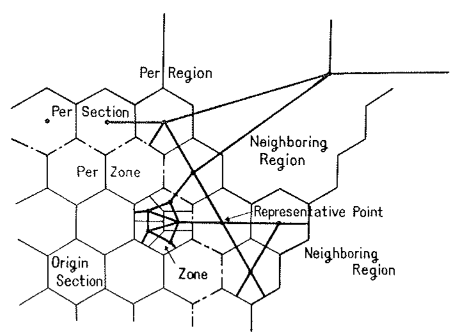


Figure 8. Approximation of network.



be parallel to and 45 cm above the ground loop.

The data transmission procedure is shown in Figure 11. The vehicle, having recognized the ground antenna by receiving the carrier wave from the ground, sends the request data, preceded by a header. The ground generates the response data and transmits to the vehicle. If the vehicle has received erroneous or invalid data, or if time is out, it sends the request data once more. If the ground detects an error in the data it received, it acknowledges the vehicle by sending invalid data. The longitudinal length of the ground antenna allows retransmission.

When the vehicle receives valid data, it locks itself and inhibits further communication until it travels a certain distance, which is prescribed by the data from the ground.

Figure 12 shows the pattern of coupling between the ground and vehicle antennas. The pattern is not symmetric because of the body effect of the vehicle; it varies vehicle by vehicle. The vehicle is given a higher receiving threshold (relative to the level at the center of the ground antenna) than the ground, in order to assure that the ground is ready to receive when the vehicle sends data after detecting the carrier from the ground. By this arrangement of level setting, we can do without the trigger loop that was employed in ERGS (3). The principal values of the transmission level are shown below:

Item	Vehicle to Ground	Ground to Vehicle
Antenna transmitting current (mA)	75	14
Field strength at receiving antenna (V/m)	0.2	1.9
Reception (mV)		
Induced voltage	2.5	0.6
Receiver threshold	0.5	0.3

Figure 9. Guide table.

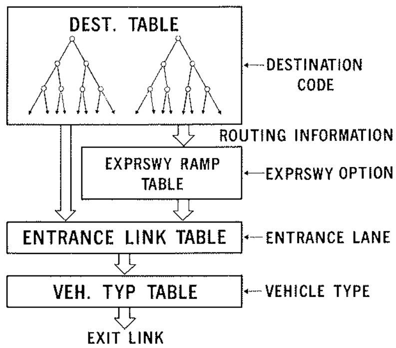
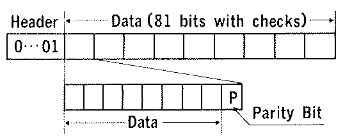


Figure 10. Frame configuration of vehicle-ground transmission.



A vehicle unit consists of a vehicle antenna, a transceiver and control, a display unit, an encoder, a power supply unit, and such accessories as wire harnesses and an odometer senser. The transceiver and control stores the data received and sends the messages to the display unit in accordance with the timing instruction sent from the ground.

Figure 13 shows a diagram of the roadside equipment. The roadside equipment receives geometric information about the intersection from the center at the initial stage and the guide table every 15 min (Figure 14). When the roadside equipment receives request data from a vehicle, it looks up the guide table, by indexing the destination, expressway option, vehicle type, and the entrance lane, and obtains the exit link. The instruction to the vehicle is obtained by indexing the entrance lane and exit link and looking up the intersection geometric table.

TRAFFIC NETWORK SIMULATOR SYSTEM

The Traffic Network Simulator System (TNSS) is a special-purpose computer to search optimal routes (minimum-time routes) in a road network. The TNSS

Figure 11. Procedure of vehicle-ground transmission.

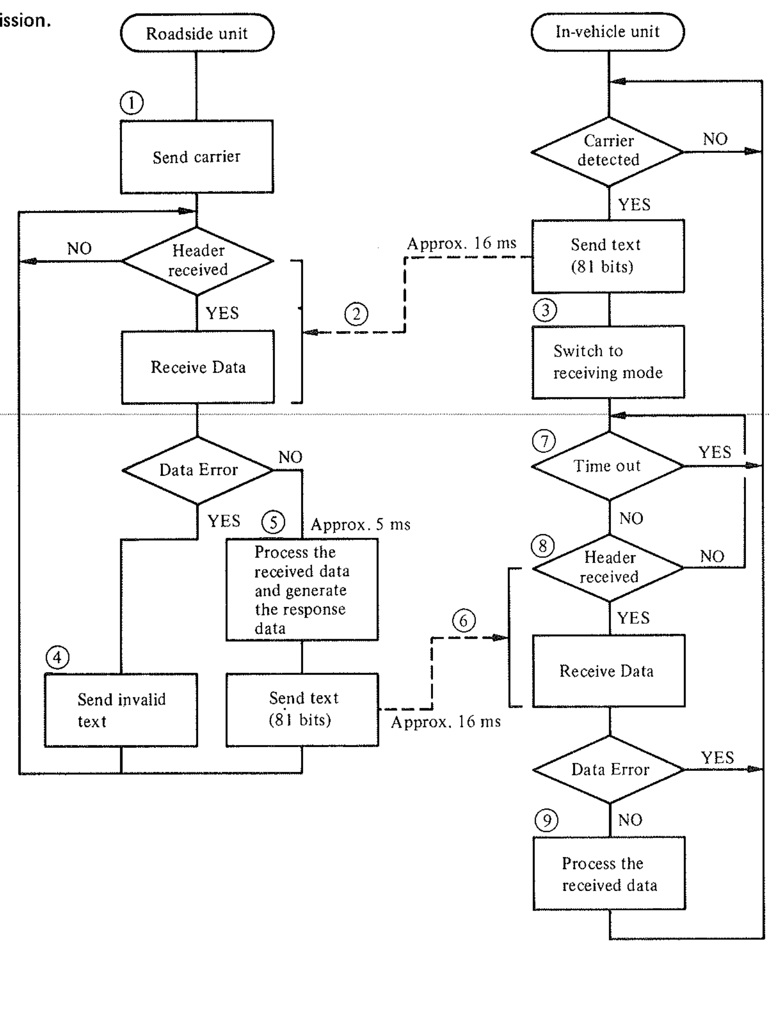


Figure 12. Coupling pattern between vehicle and ground antennas and setting of threshold level.

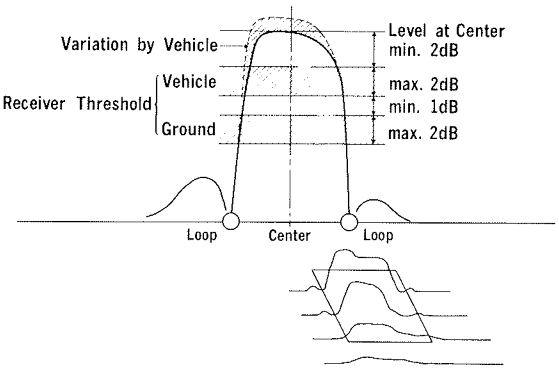


Figure 13. Diagram of roadside equipment.

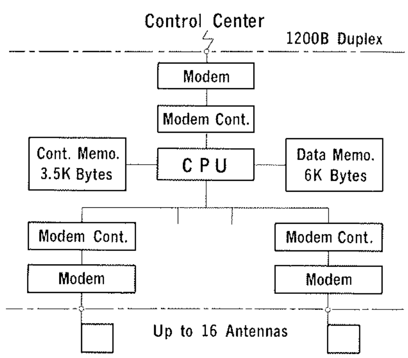
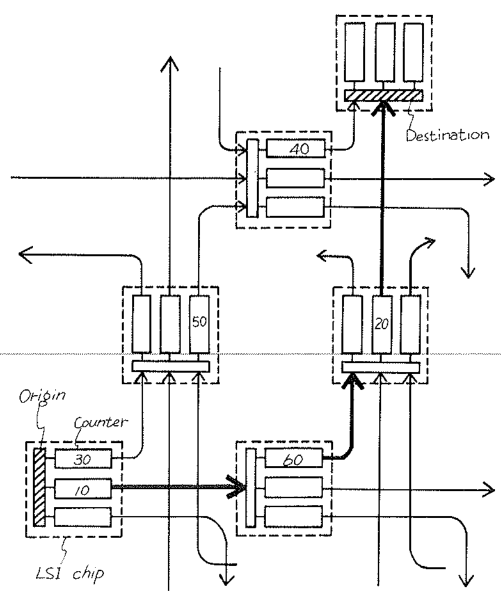


Figure 14. Principle of route search in TNSS.



has a large-scale integration (LSI) network in which newly developed LSIs are connected in a way analogous to the route guidance road network of the pilot area and its circumference. The optimal routes are computed by simulating trips in the actual road network by means of the propagation of electric pulses in the circuit, as is shown in Figure 14. TNSS executes the following information processing every 15 min:

1. Prediction of traffic flow: TNSS predicts the condition of traffic flow in the road network up to 1 h ahead based on past and recent traffic flow data (collected through the vehicle detectors). Then it computes the arc travel time for every arc of the road network.
2. Search for optimal routes: TNSS searches for the optimal routes from one origin to all destinations by using the travel-time data computed above. Repeating this process, the optimal routes are determined from all origins to all destinations.
3. Formation of guide tables: TNSS compiles the results of the optimal-route search in the form of the guide table for each intersection. Figure 15 shows the configuration of TNSS; the traffic network is an LSI network analogous to the actual road network.

In the pilot system, the route search can be performed either in the general-purpose computer mode, which adopts the algorithm described above, or in the special-purpose hardware mode, by means of TNSS.

ROADSIDE RADIO

Leaky coaxial cable (LCX) about 400 m long is wired at 5-m height along the street for broadcasting the urgent information subsystem. As a vehicle passes by this stretch of the street, the broadcast is received through an adaptor attached to the automobile's radio. Unlike regular commercial radio broadcast, the urgent information reaches only the vehicles in the vicinity of the LCX. It is thus possible to broadcast different messages in different places at the same time (Figure 16).

There are two classes of information priority. The class is identified by means of a pilot tone superimposed on the voice signal. When the class is of the first priority, the adaptor makes the vehicle's radio receive the urgent information, even if the radio has been turned off or tuned to a commercial broadcast. When the class is not of the first priority, the information can be heard only by drivers who have turned on a selecting switch on the adaptor.

The LCX antenna is divided into two sections. Different pilot tones are fed to both sections. The adaptor can recognize the direction of movement by the sequence of the pilot tones. In this way it is possible to provide the information only to the vehicles running in the direction the system specifies.

The voice message of broadcast is automatically synthesized according to the button operation by the operator and sent to the roadside transmitter via leased lines. The frequency used is 450 MHz, and the output power of the transmitter is 2 W. The roadside antennas are installed at nine locations.

ROADSIDE ROUTE DISPLAY

An approximated road network is shown on the roadside route display board (Figure 17). The information is displayed by changing the colors of the links of the network. There are three categories of display:

1. Display of congestion: the colors of the links change to yellow or red according to the degree of congestion,
2. Display of optimum route: the links along the recommended route are green, and
3. Display of an accident: the location of a traffic accident is indicated by a red link, and a red light flashes at the corner of the board.

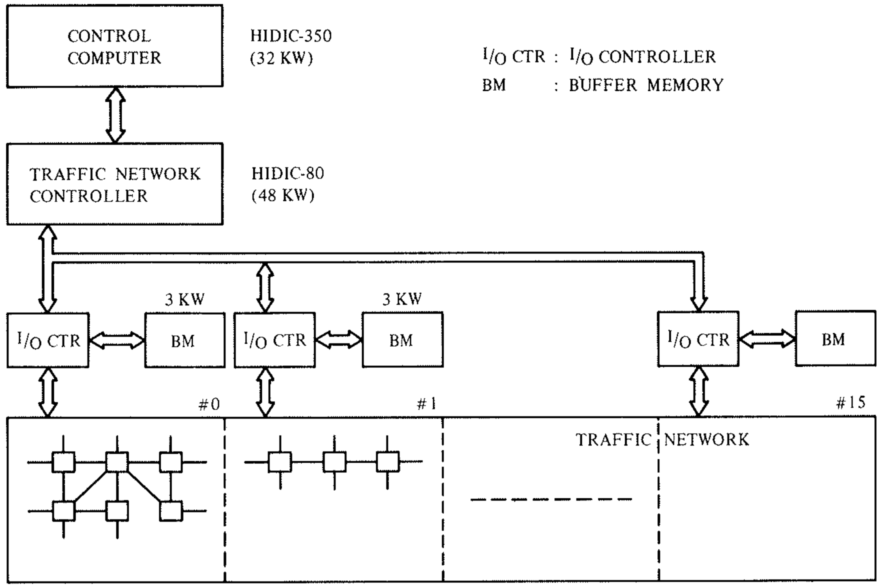


Figure 15. Configuration of TNSS.

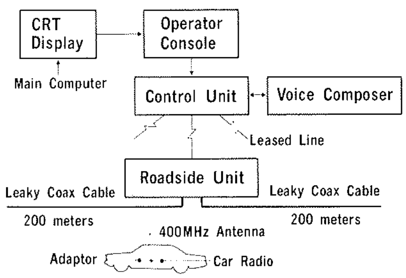


Figure 16. Configuration of roadside radio system.

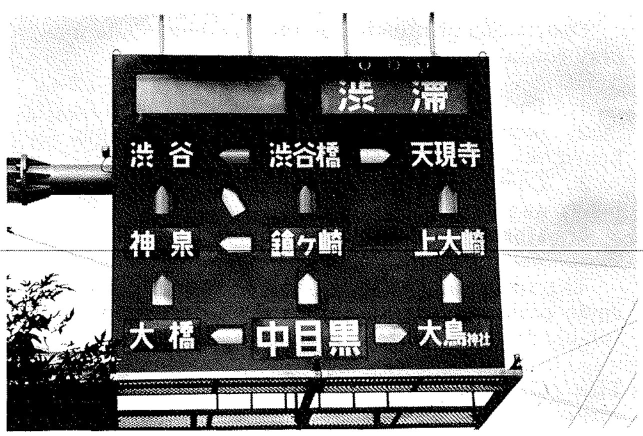


Figure 17. Roadside route display board.

The link on the board is a rotary drum that is divided longitudinally by four colors.

MILLIMETER-WAVE COMMUNICATION MODE

For communication between vehicles and roadside units, it is anticipated that a need to transmit more extensive information will arise in the future. Transmission of a large volume of information (2 M bits/s) over a millimeter-wave band (60 GHz) is being tested at one of the intersections in the pilot test area. By using the millimeter-wave communication mode, it is possible to transmit 160 kilobits of visual information to a vehicle traveling up to 100 km/h.

For this pilot test system, transmission data are two 128x128-dot pictures and eight 256x256-dot pictures compressed to ¼ in data length. An on-board television tube displays, by using two 128x128-dot pictures, a drawing of the approaching intersection on which a flashing arrow indicates the direction to be taken (Figure 18). At the same time, eight different images (256x256-dot pictures) can be reproduced on recording paper in an in-vehicle recording device. The vehicle antenna is fixed on the roof of the automobile. The ground antennas are installed under a pedestrian bridge (5, 6).

CONTROL CENTER

The control center has a control room (Figure 19), a machine room, and a pilot test headquarters. In the control room, equipment for display [including cathode-ray-tube (CRT) display] and operation are installed, and in the machine room are one large-scale computer (NEAC2200/375), four minicomputers (NEAC3200/70), one traffic network simulator with a control computer (HIDIC350), and some other control units.

Man-Machine Interface Equipment

The major equipment in the control room are the wall display and an operating console. The wall display presents information that all operators require and is controlled by the supervisory operator. The devices of the wall display and the information carried are shown below.

Device	Information
Central screen display (2.0x1.5 m)	Pilot area maps, with a video-projecter in the rear
Color character CRT	Roadside unit status, indicated by the color of the unit number
Flap-type indicator	Title of map projected on the screen

Figure 18. Picture received in the vehicle by millimeter-wave communication.

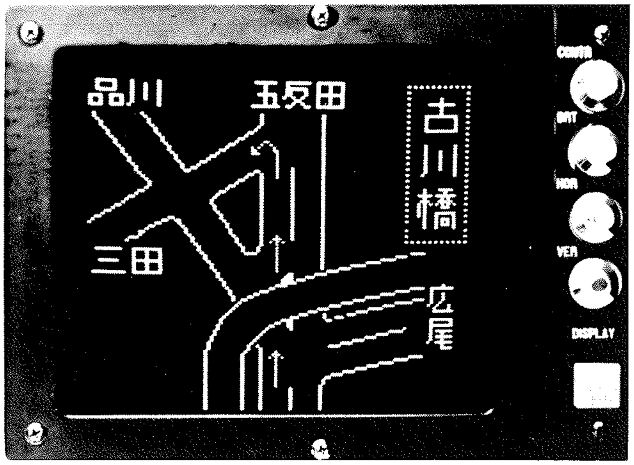
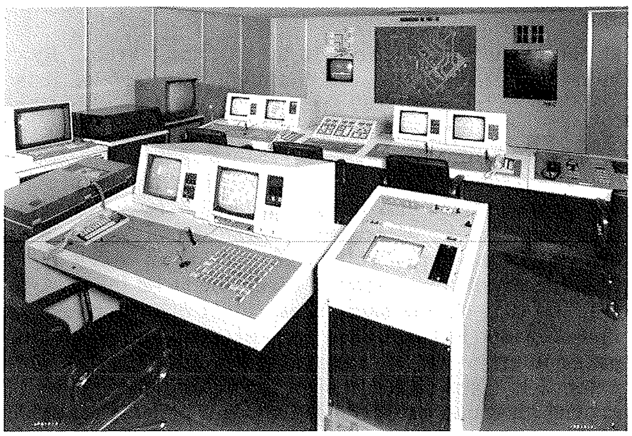


Figure 19. Control room.



Device	Information
Light-reflecting dot-matrix indicator	Date and time
Lamp indicator	Individual computer status
Lamp panels	Functions in operation, weather, and route-search mode

There are four operating consoles: one for the supervisory operator; one for the operator of the route guidance, driving information, and public-service-vehicle priority functions; one for the operator of the roadside route display; and the last for the operator of urgent information messages. These consoles are all equipped with a character CRT, function keys, typewriter keys, and lightpens. The first two are also equipped with a graphic CRT, joy sticks, flap-type indicators, telephones, and radio transceivers.

The maps that are shown on the central screen display and the graphic CRTs are listed below, along with the information they carry; each operator can display any of the maps on his or her own CRT:

1. Road map of the entire area: (a) degree of congestion (light = green, heavy = yellow, congested = magenta), (b) location of test vehicles (not present = green, present = magenta), (c) flow rate of test vehicles (low = green, medium = yellow, high = magenta), (d) vehicle tracking (vehicle 1 = red, vehicle 2 = yellow), and (e) optimal route (route 1 = red, route 2 = yellow);
2. Zoomed-up map: degree of congestion and the location and identification of test vehicles; and
3. Intersection maps: geometric figure of each intersection.

Control Operation

The control operation has a two-level hierarchical structure. The lower-level control operation is for the monitoring and control of each of the five functions of this system, e.g., route guidance, driving information. The higher-level one is for the supervisory control of the entire system. Operations performed on the supervisory console are

1. Initial system set-up,
2. Starting and stopping the overall operation or partial function of the system,
3. Changing system parameters and configuration,
4. Monitoring traffic condition, and
5. Monitoring system and device status.

Operations performed on the route guidance, driving information, and public-service-vehicle priority console are

1. System function interventions after a traffic accident,
2. Roadside units' status diagnosis,
3. Monitoring traffic condition, and
4. Monitoring system and device status.

Operations performed on the urgent information console are

1. Requesting recommendation for broadcast messages from computer,
2. Setting a message for each roadside unit, and
3. Monitoring system and device status.

Operations performed on the roadside route display console are

1. Requesting recommendation of displays,
2. Setting a display pattern for each roadside board,
3. Confirming the remote station's acknowledgment, and
4. Monitoring system and device status.

The supervisory console can be substituted for the route guidance, driving information, and public-service-vehicle priority console.

THE PILOT STUDY

The pilot test has been carried out since October 1977. The initial three months of the one-year test period were dedicated to long-term trial operation of the system and to collection of information in regard to the characteristics of traffic flow in the test area.

Besides the evaluation of route guidance performance, data were obtained on such items as capability of manual intervention in route selection, computing time for route calculation, and the effect of network approximation. The visibility and comprehensibility of the display were measured, and drivers' opinions were collected.

The performance of route guidance was measured by comparing the travel time between guided and nonguided

Figure 20. Selected OD pairs for evaluation.

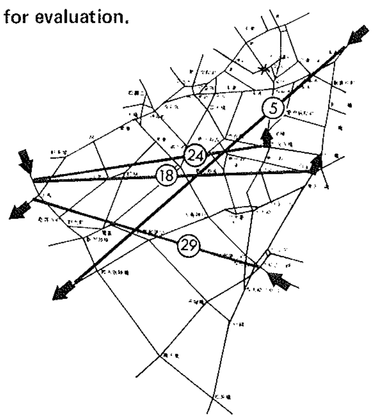


Table 1. Comparison of travel time for guided and nonguided vehicles.

Pair	Mean Travel Time(s)	Advantage Factor	Reduction of Travel Time (%)
24		76.3	15.5
Guided	1239		
Nonguided	1467		
29		72.1	9.4
Guided	1327		
Nonguided	1464		
5		76.1	10.8
Guided	1763		
Nonguided	1976		
18		75.0	9.3
Guided	1657		
Nonguided	1837		

vehicles. About 1000 trials were made between seven origin-destination (OD) pairs (Figure 20). As is shown in Table 1, travel time has been reduced by 9-15 percent.

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