are displayed. Highway agencies are now emphasizing the need for closed-circuit television as an integral part of urban traffic advisory and incident management changeable message sign systems—not as a primary surveillance technique but as a means for rapidly validating incidents and determining the nature and scope of the problem (5).

One facet that is often overlooked during the design, development, and implementation of a traffic control system is hardware maintenance. Relative to the route guidance system, it is quite apparent that hardware will be installed in various local and state jurisdictions. The question that arises concerns the guarantee of adequate system maintenance. Assuming that each city will have the responsibility for maintaining the system within its own local jurisdiction, some cities may perform better than others because of attitude, availability of money, and better-qualified personnel. A motorist traveling crosscountry and following a given route would expect to have continuous information. What safeguards can be provided so that the motorist does indeed have continuous information, or what can be built into the system to at least make the driver aware that the system may be inoperative within a given stretch of highway?

Even with our on-road changeable message sign systems, highway agencies are concerned with the lack of funds to purchase replacement parts. Another concern is the long delay in having components repaired by the manufacturer. Still another concern is the unavailability of replacement parts. Incorporating more off-the-shelf components into the route guidance system may help somewhat, but this is not the total solution to the potential maintenance problem.

What safeguards and provisions will be made during partial system failures, either at an intersection point area or along a segmented link of the primary or alternate route? How will the driver be routed back to the primary facility if there is a system failure while the motorist is on the alternate route? The system design will have to address these questions.

THE "FORGIVING" SYSTEM

A "forgiving" system must also be considered. For example, assume that a driver who is being directed along an unfamiliar alternate route did not make the turn according to the display. It would appear that there would be a need to alert the driver and provide instructions about how to return to the scheduled route.

Before a driver diverts, he or she needs the assurance that the route will lead to the final destination or return the driver to a primary facility (1). One approach to provide this assurance is to continuously display the final destination while the driver is traversing the primary or alternate route. Thus, the driver will be assured that this route will lead to his or her destination. When the destination name disappears from the display, it could be an indication that the driver has failed to follow the instructions given.

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Feasibility Study of Route Guidance System

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The Comprehensive Automobile Traffic Control (CAC) Project was started in 1973 as a six-year project sponsored by the Agency of Industrial Science and Technology, Ministry of International Trade and Industry. The aim of this major project is to develop a comprehensive system for controlling the flow of vehicular traffic through the use of the most up-to-date computer and other technology for monitoring and controlling traffic in order to improve overall traffic conditions by reducing accidents, congestion, and air pollution and to relieve drivers of unnecessary mental stress. This paper presents some results of the feasibility study of this CAC system. Since route guidance plays the most important role in the CAC

system, a detailed explanation is given of the route guidance subsystem and its guidance algorithm, which is based on the results of computer simulation. This report also discusses the effects that might be expected from introducing the CAC system in an area of Tokyo that contains 1500 intersections. In particular, this report closely scrutinizes the important route guidance subsystem, providing a quantitative analysis of the possibilities for easing congestion and achieving various other effects. A general review is made of the costs and benefits of such a system.

The growth of large Japanese urban centers in recent years has resulted in a greater volume of traffic, and a number of social problems have emerged—traffic congestion, an increased number of traffic accidents, and air pollution—whose resolution has by now become a priority task. The Comprehensive Automobile Traffic Control (CAC) system is a new development in traffic technology that seeks a solution to these problems.

The CAC technology project, sponsored by the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry, was initiated in 1973 to cover a six-year research period with a budget of 7 billion yen [¥220 = $1.00 (August 1979)]. The basic function of the CAC system is to link individual motor vehicles to a central traffic control facility through communication devices that provide drivers with pertinent information concerning surrounding road conditions and that serve to regulate the general flow of traffic.

The CAC system is broken down into five subsystems for route guidance, driving information, traffic incident information, route display board, and public vehicle priority. The pilot test (1) was carried out to evaluate these subsystems' functions. In parallel with this pilot test, the feasibility study focused on route guidance of the CAC system.

STUDY OF ROUTE GUIDANCE METHODS

In the CAC system, the route guidance subsystem that provides information to drivers on the optimum route to their destinations plays the major role. The driver will input a destination code number into a unit mounted in the vehicle (see Figure 1) and, on approach to major intersections, will receive a visual display of route guidance instructions to turn left or right or to proceed straight ahead. By reacting appropriately to this information, the driver will avoid areas of traffic congestion and reach his or her desired destination by the optimum route.

The optimum route is defined as the one that, in terms of time, distance, or economy, offers maximum advantages given the existing traffic conditions. Thus, whenever traffic volumes on a specific route reach a certain level and travel efficiency along that route decreases because of congestion, that route is no longer considered optimum and drivers who normally use that route will be instructed to use alternative routes.

Providing drivers with route guidance information will help to create a more even distribution of traffic volumes on the road network, thereby increasing the efficiency of automobile transport. On the other hand, in order to give such information it is necessary to find the optimum route for each driver. This requires a route guidance algorithm.

One of the merits of route guidance is that, if the number of drivers following the guidance instructions given is small, those that follow the instructions will arrive at their destinations sooner than those who do not. A guidance algorithm for this situation is already established as the shortest-path method (2) with link cost as input.

As the percentage of drivers influenced by route guidance increases, however, the general traffic situation develops in ways that result from the guidance. Also, the aim of a route guidance system is not primarily to benefit the individual but to alleviate congestion, a social benefit. Thus, the aim of guidance is to satisfy the driver's origin-destination (OD) requirements by selecting the route that keeps congestion as low as possible. For one OD pair, therefore, the optimum route may not be only one route.

The control system, of course, has dynamic characteristics, and a need thus arises for considering algorithms that reflect time changes in the environment.

In considering the following route guidance algorithms, analyses were carried out by viewing as parameters the guidance percentage, the indicated route computation cycle, the OD pattern, and other factors on the basis of methods of equal-time allocation and shortest-route guidance, as well as partial corrections of those two methods.

Outline of Analyses and Tools

In order to consider a comparison of route guidance methods, traffic-related data were put into order, various models and simulators were prepared, and analyses were conducted. Figure 2 shows an outline of those activities.

Trip Structure Model

The trip structure model was a static traffic assignment model based on the shortest-path algorithm, and it treated the road network data, OD data, zoning data, and other data related to traffic in Tokyo systematically. The data were put into order for use as a data base, which provided estimated values of the present breakdown of OD trips and average traffic volume for any link. Through this model, therefore, it is possible to obtain OD, network, and other data related to Tokyo's 23 wards. A pilot area was selected for analysis in order to consider in detail the route guidance methods. Figure 3 shows a scissored network chosen for the analysis.

Route Selection Model for Nonguided Vehicles

In order to conduct a detailed study of route guidance methods, we must construct a model of the special characteristics of traffic flows when drivers choose their own routes.

First, by use of the kth path method (3), a route generator (4) that automatically picks out all the possible routes for each OD pair was constructed, and available routes that drivers may choose from the actual road network were searched.

In regard to these available routes, models that can be determined quantitatively by a multiple-regression analysis of measured data of the choices made by drivers were prepared. These models were based on the following formulation for route i ($i = 1 \sim n$):

$$d_i = w_1 r_{i1} + w_2 r_{i2} + \dots\dots\dots + w_p r_{ip} + w_c \qquad (1)$$

where

d_i = selection standards values of route i,
w_j = weight of attribute j,
r_{ij} = selection standards values of attribute j of route i,
w_c = correction, and
n = number of routes being selected.

Figure 1. Components of route guidance subsystem.

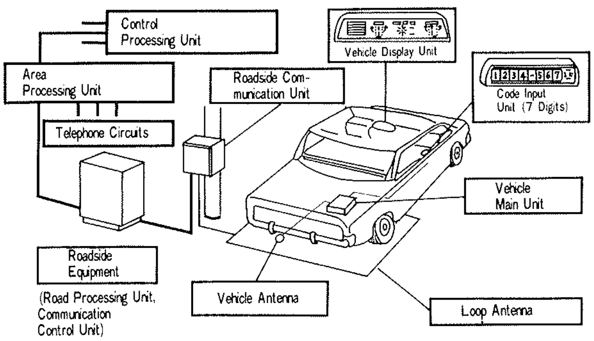


Figure 2. Flow of analysis.

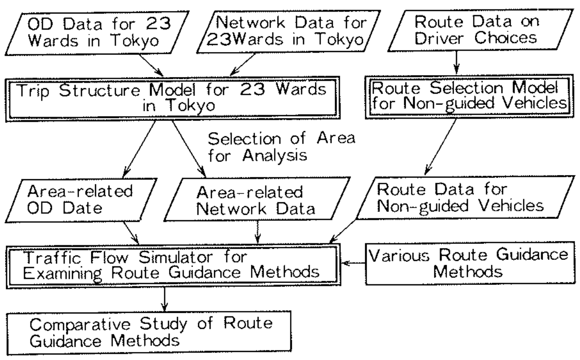
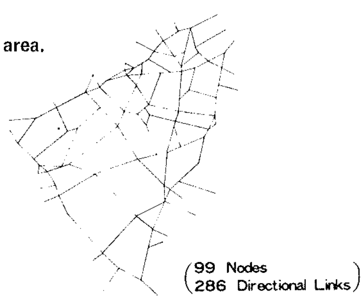


Figure 3. Scissored network of the pilot area.



In the analyses, we chose road length, number of lanes, percentage of trunk lanes, and number of left and right turns as the attributes influencing the route selection. Figure 4 shows the comparison between modeled traffic volumes and the ones actually measured. This result shows that our model fairly well represents the driver's route selection behavior.

Simulator for Examining Route Guidance Methods

In addition to the static model mentioned in the preceding sections, a simulation model is required for the investigation of route guidance algorithms for actual, dynamically varying traffic flows. This requirement has led us to the use of a simulator that incorporates vehicle movement logic on the basis of queuing concepts (5). This simulator consists of a route-computing module, a traffic-flow simulation module, and monitor control of these modules.

Queuing Logic

A vehicle is guided from the link queue toward the arc queue via the lane server and then to the following link queue via an arc server, as is shown in Figure 5. The link travel time is controlled by the lane server, while the arc travel time (intersection passing time) is controlled by the arc server.

Control of the Link Travel Time

The lane server takes into account constant-speed travel, safe head-to-head distances, and traffic signal conditions to determine the link departure time for each vehicle. The procedure for this determination is expressed by the following algorithm in which t_1 = departure time for the preceding vehicle and t' = departure time on the assumption of constant-speed travel for the vehicle in question:

1. If $t_1 > t'$, then $t = t_1$ + headway at start; otherwise $t = \max(t', t_1 + \text{safe head-to-head distance})$.
2. If t falls within the red signal period, t = the next green time + delay in starting.

Control of the Arc Travel Time

The arc server determines the arc departure time by adding to the link departure time an average constant value according to whether the motion is straight travel, a left turn, or a right turn. The model thus obtained is event oriented, and it performs a calculation whenever a link or an arc event occurs.

In this model, the effect of route guidance is obtained by simulating the traffic flow when each vehicle follows the recommended route according to the guide table at each intersection.

Simulation Experiments and Results

Route guidance methods have been examined by conducting simulations according to the following conditions and by using the above-mentioned models.

Experimental Network

A simplified pilot area (Figure 3) containing 99 intersections and 286 directional links was constructed by extraction from a trip structure model of a network of some 1500 intersections in an area of Tokyo.

OD Traffic Volume

The patterns of OD traffic volumes associated with the pilot area were estimated to be those shown in Figure 6, based on the results of the trip structure model.

Route Guidance Methods

The following three algorithms were investigated:

1. Shortest-route guidance;
2. Exponentially smoothed shortest-route guidance, which gives multiple directional indications by overlapping at a certain percentage the guide table used previously with a new guide table computed by using the latest information from the shortest-route algorithm; and
3. Equal-time guidance, which uses the incremental assignment method (6) for all OD pairs to iterate computations of link cost and shortest routes 10 times in order to determine the guide table.

Nonguided Vehicles

The route selection model described above was used to determine the routes for nonguided vehicles.

Evaluation Functions

1. Total delay time expresses the degree of congestion for the specified area, and the pattern of the changes in this measure allows a comparison of the methods, thus: $c_i - c_{i_0}$, where c_i = average time required for traveling on link i and c_{i_0} = time required for traveling on link i when there is no congestion.

2. Total travel time expresses the degree of congestion for the specified area by a single value, thus: $\sum_i t_i$, when t_i = time required for travel by the ith vehicle. As Figure 7 shows, when all vehicles have

Figure 4. Comparison of measured values and modeled values of traffic volumes.

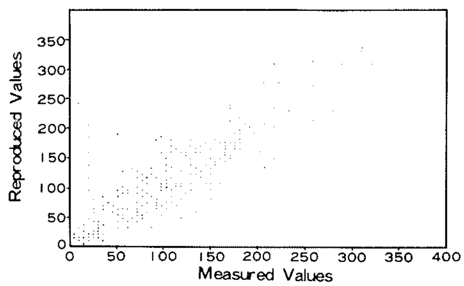


Figure 5. Model of vehicle movements.

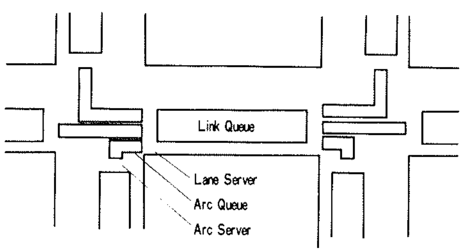


Figure 6. Pattern of OD traffic volumes.

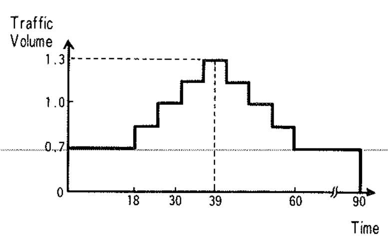
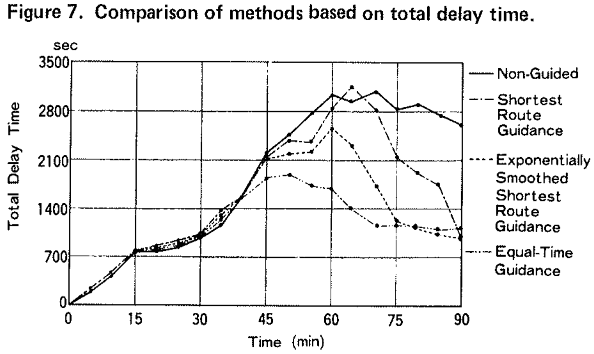


Figure 7. Comparison of methods based on total delay time.



on-board equipment, the most effective route guidance method is the equal-time method. The other methods range in order from the exponentially smoothed shortest-route guidance to the shortest-route guidance. From the point of view of practical application, the equal-time method has such problems as a large computation time and difficulty of obtaining the OD traffic volumes.

On the other hand, the exponentially smoothed shortest-route guidance and the shortest-route guidance methods are easily applied to actual situations because these two methods are mainly based on the link cost data that are directly obtained from our CAC system. We examined how the total travel time decreases as the guidance rate goes up when using these two practical methods. From the results (shown in Figure 8), we may conclude that it is most effective to use the shortest-route guidance method at a low guidance rate and to switch over to the exponentially smoothed shortest-route guidance method when the guidance rate is high.

EXAMINATION OF COST AND BENEFITS

Through the foregoing simulation experiments in the pilot area, the various route guidance methods were compared. Here a cost-benefit analysis of investments was performed on the supposition of improvements to the traffic flow if these systems were introduced to the whole Tokyo area.

Review of Benefits

A review was made of the benefits that would accrue from adoption of the route guidance subsystem, which is considered the most important subsystem in the CAC system.

Shortening of Required Travel Time

Areas A, B, and C (city center, city subcenter, and peripheral residential area, respectively) were selected as representative areas of Tokyo and the dynamic simulation was carried out to estimate the reduction in total travel time in those areas in the same manner as that mentioned above for the pilot area.

Based on these results and considering the macro characteristics of traffic flow in Tokyo, the overall reduction in total travel time in Tokyo was estimated to be about 6 percent on the average. If the time saving from this shortening of travel time is expressed in money terms, the total yearly benefit is computed to be approximately ¥80 billion.

Fuel Economy

By using the relationship between gasoline consumption and vehicle speed, the overall fuel economy for Tokyo's 23 wards was estimated to improve by approximately 3-7 percent according to the location and time of day. Therefore, the average fuel savings for the daytime period (7:00 a.m. to 7:00 p.m.) was taken to be 5 percent. Expressed in money terms, this improvement amounts to benefits of about ¥9 billion.

Reduced Air Pollution

According to the simulation tests, it can be expected that introducing the route guidance subsystem will result in reduced exhaust emissions of approximately 6.5 percent for carbon monoxide, 6.2 percent for hydrocarbons, and about 0.4 percent for nitrous oxides (7).

Figure 8. Dependence of total travel time on guidance rate.

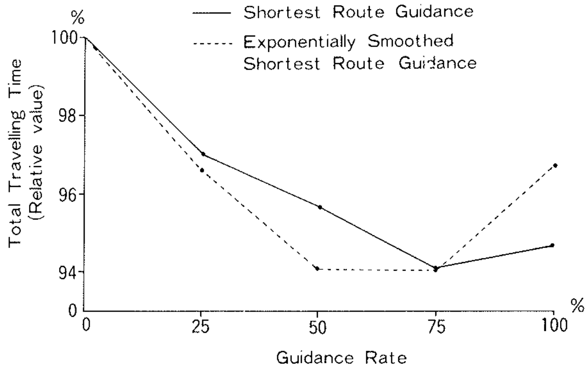
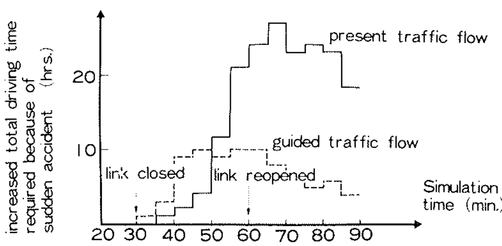


Figure 9. Effect of route guidance in case of sudden accident.



Keeping Close Schedules

Simulation test results indicate that use of the route guidance subsystem will lead to a tendency for reductions in average driving time required and reduction of variance in arrival times. For example, a random sample of 27 ODs (average of 220 trips per OD pair) was taken, and the distribution of required driving time for each OD pair was examined. In this case, the variation factor was found to decrease from 0.25 to 0.15 by introducing route guidance.

Reduction of Traffic Accidents

Based on Metropolitan Police Board data listing causes of traffic accidents in 1976, approximately 40 percent of the accidents that year resulted from factors that would be offset by using the route guidance and driving information subsystems. If 10 percent of these accidents could be prevented by using these two subsystems, the benefits could be expressed in money terms as follows [data on value of social loss obtained from Japan Research Society for Transport Policy (8)]:

[Traffic deaths (300/year) + traffic injuries (35 000/year)] × ¥2.46 million/person × [rate of guided roads (0.6)] × 0.04 = ¥2 billion/year

Preventing Traffic Congestion Caused by Sudden Accidents

When a sudden traffic accident blocks a roadway, the required driving time for vehicles in the vicinity increases sharply. It was ascertained from simulation that the route guidance subsystem has the effect of greatly preventing this type of traffic congestion. An example is shown in Figure 9, which depicts the closing of a link near Tokyo Station by an accident. The link is disconnected from the system and simulation is carried out. The graph shows the resultant increase in total driving time.

Review of Costs

1. Preconditions for estimates: Equipment needed for the route guidance subsystem for the 1500 intersections in Tokyo's 23 wards is shown below.

Item	Number of Units Needed
Route guidance roadside units	4 units/location x 1500 locations = 6000 units
Loop antennae	4 x 2 units x 1500 = 12 000 units
Main-area computers	1 set
Local-area computers	32 sets
Communications lines	4 x 1500 = 6000 lines

2. Cost: The initial investment costs and annual operating costs for ground facilities are projected from the pilot experiment data as shown below:

Item	Cost (¥000 000 000s)
Investment costs	
Construction: survey, roadside units, loop antennae, communications lines	4.74
Manufacture of equipment: roadside units	7.20
Central control unit	
Office remodeling	0.82
Computer purchase	5.45
Software preparation	0.20
Total	18.41
Annual operating costs	
Central control	
Office rental	0.44
Operations	0.2
Personnel	0.13
Roadside units: upkeep	0.6
Use of leased lines	0.86
Total per year	2.23

Besides these costs, there is also a need for on-board equipment in the route guidance subsystem, which is estimated to be about ¥30 000/vehicle.

Overall Evaluation

The following formula was used to calculate the expected costs (TC) and the possible benefits (TB) over x number of years following introduction of the route guidance subsystem.

$$TB = \sum_{i=1}^{x} B(i)/(1+r)i \qquad (2)$$

$$TC = IC(x) + RC(x) + CC(x) + RCC(x) \qquad (3)$$

in which

$$IC(x) = (IC_o) \sum_{N=0}^{\frac{x}{n_{ic}}} (1+r)^{-N \times n_{ic}} \qquad (3ai)$$

$$N = (i/n_{ic})\ i = 0 \sim x \qquad (3aii)$$

$$RC(x) = (RC_o) \sum_{i=0}^{x} (1+r)^{-i} \qquad (3b)$$

$$CC(x) = (\alpha \times S) \sum_{i=0}^{x} \{\alpha'(i) + [\alpha(i)/n_{cc}]\} \times (1+r)^{-i} \qquad (3c)$$

$$RCC(x) = (RCC_o \times S) \sum_{i=0}^{x} [\alpha(i)]\ (1+r)^{-i} \qquad (3d)$$

Figure 10. Rate of installation of in-vehicle units.

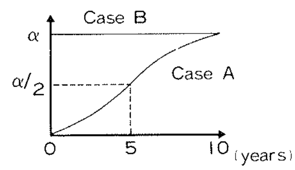


Figure 11. Annual trends in total costs and benefits.

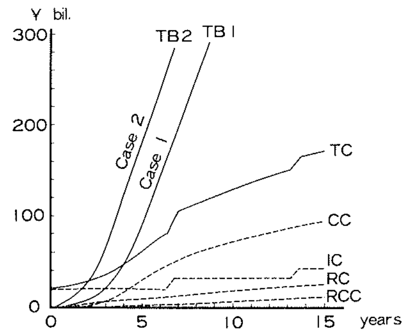
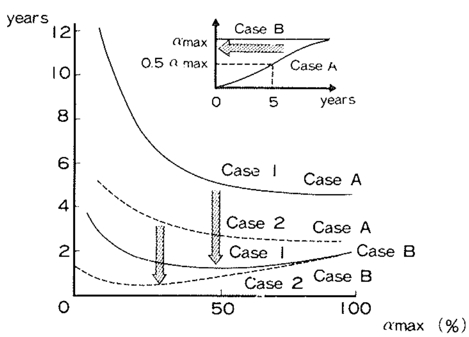


Figure 12. Social repayment years and the final diffusion rate of in-vehicle units.



where

IC_o = initial investment costs = ¥20 billion;
RC_o = annual operating costs = ¥2.5 billion;
RCC_o = annual cost of upkeep per in-vehicle unit = ¥1000/unit;
α = in-vehicle unit cost, including installation = ¥30 000/unit;
s = total number of vehicles in target area = 1.8 million;
r = social discount rate = 6 percent;
n_{cc} = durability of in-vehicle equipment = 6 years;
n_{ic} = durability of other than in-vehicle equipment = 7 years; and
$\alpha'(i)$ = rate of increase of automobiles that have in-vehicle units [$\alpha(i)$ after i years].

Two additional assumptions are made for this overall evaluation.

Reliance of Benefits on Guidance Rate (β)

The benefits are viewed only in terms of reduction of required driving time. Accordingly, by using the information from Figure 8 that expresses the reliance of the rate of reduction in required driving time on the guidance rate, the following formula will give us an approximation of the benefits:

$$B(\beta) = 80 \times (2-\beta) \times \beta(\text{¥}000\ 000\ 000\text{s/year}) \quad (4)$$

Installation Rate of In-Vehicle Units (α) and Guidance Rate

Figure 10 shows two rates of installation of in-vehicle units. Case A shows a logistic curve that in five years reaches $\alpha/2$ and eventually reaches close to α. Case B shows a step function in which α is reached quickly in the first year.

Two other cases are examined: case 1, in which the percentages of β and α are equivalent, and case 2, in which in-vehicle units are installed in the target area beginning with vehicles that drive longer distances. The evaluation used Equations 2 and 3 and was based on the assumptions mentioned above. Figure 11 shows the annual trends for TC and TB in cases 1 and 2.

The number of years required for TB to equal TC is called the social repayment years. Figure 12 shows the relationship between x number of social repayment years and the final diffusion rate of in-vehicle units. If the final diffusion rate is supposed to be 100 percent, the social repayment period will be two to four years. Figure 12 shows that, even if the final diffusion rate of in-vehicle units is less than 100 percent, this system offers considerable benefits that meet the initial investment and operating costs within a couple of years.

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