Risks have been pinned on the development of intelligent systems for road traffic as a way of solving road traffic safety and other issues. To be sure, work is moving ahead with the incorporation of intelligent systems into automobiles, but with automobiles alone, there are limits in areas such as environment recognition. Compensation for the limits imposed by automobiles can be provided by the support given to environment recognition and related areas of road infrastructure. This paper examines the special features of vehicles and road infrastructure, and describes what role is played by roads and what role is played by vehicles. On the basis of the observations made, road-vehicle cooperative support systems called “smart cruise systems”, which are currently being developed, will be introduced and the expected effects of these systems will be outlined.

Road transportation by way of automobiles is a very convenient means of transportation, and it contributes significantly to elevating people’s lives. However, some serious social issues have been created as the number of vehicles has continued to increase. They include traffic accidents, congestion and adverse effects on the environment. In particular, the problem of traffic safety is a serious and urgent one, and one which requires some radical solutions. To this end, some improvements in driving systems and in vehicle body construction have been made in automobiles, and these improvements have had a profound effect. In Japan, traffic accidents used to result in over 10,000 deaths annually although in more recent years this figure has been reduced to a figure ranging from 9,000 to 10,000 deaths. This trend notwithstanding, the number of traffic accidents that occur has increased. Almost all traffic accidents are caused by human factors, and this means that improvements in the capabilities of drivers are needed. Driver education courses are held with this in mind but they still fall short. It is necessary to prevent the occurrence of accidents by compensating for the errors made by drivers. It is from this perspective that work has been conducted on incorporating intelligent systems into automobiles. Among the systems emerging on the market are systems which can detect the cruising environment including the distances between an automobile and obstacles, sound a warning to the driver or automatically adjust the distance between vehicles, and systems which detect the white lines on the road that serve as lane markings and sound an alarm when an automobile strays out of its lane. However, there are limits as to how far intelligent features can be incorporated in automobiles themselves, and these limits must be offset in some way. Road infrastructure has the potential to offset the limits of automobiles, and hopes are pinned on road-vehicle cooperative driver support systems.

Road traffic consists of three elements: the people (the drivers), the automobiles, and the roads. In order to improve road traffic safety, all three elements must be elevated. At the present point in time, efforts are underway to make improvements in the areas of these elements but each is accompanied by issues and limits.

2.1 Improvements in the capabilities of drivers
First comes information-based education and hands-on training programs which have been undertaken for
improving the capabilities of drivers. One example of information-based education is “danger prediction training” in which drivers look at traffic scenes using photographs and other materials and consider the dangers which can be expected to occur. In terms of hands-on training, driving courses are held where a driving simulator is used to enable drivers to experience for themselves a simulation of dangerous scenes and where test sites are used to give drivers the actual experience of driving on slippery road surfaces. These have produced their own due results. However, since it is up to the drivers to avail themselves of these opportunities and since there are restrictions on the kinds of environments where these courses can be implemented, the education and training are not always adequate. Since some serious problems such as the aging of society loom ahead in the future, it is necessary to support the diversification of driver capabilities. This leads to the need for cruise support systems to support drivers.

2.2 Improvements in the functions of automobiles

Second come the improvements in the functions of automobiles. Some major contributions to reducing collision damage have been made by air-bags and impact-absorbing vehicle bodies but these improvements cannot reduce the occurrence of traffic accidents themselves. Some improvements involved with driving such as antilock braking systems (ABS), vehicle stability and active control over the dynamic characteristics of vehicles have been made. These help to augment the driving capabilities of drivers and contribute to reducing the possibility of accidents. Furthermore, more and more systems which involve installing sensors in automobiles to detect the cruising environment and predict the occurrence of accidents are being used. These include systems which detect the distance between vehicles and warn of collisions, systems which detect the white lane markings on roads and warn the driver when an automobile strays out of the lane, and systems which detect vehicles on both sides and behind an automobile and warn of the dangers of changing lanes. Such systems are believed to contribute greatly to preventing traffic accidents but their detection capabilities are subject to limits as will be described later.

2.3 Improvements in the roads

Third comes road improvements. Roads have been continuously upgraded to ensure the safe and efficient travel of vehicles from Roman times when the roads were paved with cobble stones to today’s autobahns of Germany and the interstate highways of the United States. Road improvements with curves or intersections shaped to make it easy to drive along or through them have played a major role in improving safety. The permeable pavements of recent times greatly improve visibility in rainy weather. Impact-absorbing guard rails and other damage-reducing facilities have also been installed. Yet restrictions on usable land and regional, meteorological and environmental conditions impose limits on providing a satisfactory road environment.

For the reasons described above, there are limits on one of the support systems alone for the three elements—people, vehicles and roads—and the need has arisen to press ahead with different approaches such as mutual cooperation between these aspects.

A straightforward example in which roads and automobiles affect each other will now be presented. When the authors visited the Mercedes-Benz (Daimler Chrysler) Museum in Germany, they realized that the steering wheel was placed on the right in Europe’s first cars. This does not mean that cars drove on the left in those days: they drove on the right-hand side of the roadway. The first cars were horse-drawn carriages equipped with automatic power. The drivers of these cars were seated on the same side as the drivers of the horse-drawn carriages. The roads at the time were not very well maintained, and it was necessary for drivers to keep their attention on the shoulder of the roadway while driving, and the drivers (of both the carriages and cars) were seated on the right side which was the road shoulder side for traffic keeping to the right-hand side of the road. In later years, roads became better maintained along with the significant improvements in the performance of cars. Once the roads were improved, it became more important to recognize oncoming cars and the conditions ahead on the road than pay attention to the shoulder of the roadway. At this point, placing the driver’s seat on the left-hand side (of the center of the roadway) would facilitate recognition to a greater extent. As a result, the driver’s seat was moved to the left side. This is what the authors heard at the Mercedes-Benz Museum. The same is probably true for the development of expressways specifically designed to be used by automobiles which happened together with the development of vehicles that could travel at high speeds. In this way, the development of roads and automobiles has been interrelated. The present time is an age in which telecommunications, electronics and other new technologies are helping to carry forward this relationship between road and automobiles to a new level.
3.1 Features of on-board systems and infrastructure-based systems

The basic functions for driving a vehicle are visual recognition, judgment and operation. The features of the road infrastructure and on-board systems for supporting these functions by mobilizing electronics and information technology are listed below. Table 1 compares the features of on-board systems and infrastructure-based systems.

(1) Features of on-board systems
On-board systems are suited to the acquisition of information around automobiles but incapable of obtaining information at distant points. On-board systems have to process information immediately after detecting obstacles. They can be used anywhere. Since they are subject to many restrictions on visible angles and processing times, they tend to be easily affected by the weather, and the meteorological conditions under which they can be used are limited.

(2) Features of infrastructure-based systems
Infrastructure-based systems are capable of acquiring information on blind spots seen from an automobile. Infrastructure-based systems are able to detect information far from an automobile, so they have enough information processing time. They are more advantageous in terms of visible angles (installation height, breadth of field of view, etc.) for acquiring cruising environment information, signal processing times and linkup with other information systems. However, the locations where they can be used are limited to the locations where the infrastructure is actually installed. They have minimal restrictions on visible angles and processing times so that it is easy to construct systems which are minimally affected by the weather. On-board systems and infrastructure-based systems both have their own suited and ill-suited functions, and it would be difficult to create an automatic traffic system which can be used safely and risk-free using systems in one of these categories alone.

3.2 Examples of limits imposed on on-board systems

As shown in Figure 1, a hypothetical case in which a vehicle is traveling around a curve with a radius of 100 meters is now presented. The road is 3 meters wide, and a wall or other blind area is assumed to be positioned one meter on the inside of the curve. In this case, distance (visibility) L with an unobstructed view of the road center position is about 50 meters. If the vehicle is assumed to be traveling at 50 kph, it will cover a distance of 50 meters in 3.5 seconds. The lateral acceleration for traveling round a curve with a radius of 100 meters at a speed of 50 kph is approximately 1.9m/s² (approx. 0.2G) which is not a particularly high speed.

Exactly how this visibility affects the safety will now be examined. Figure 2 shows the correlation between the time taken to discover obstacles and the possibility of avoiding an accident. This figure is the result of the study and research done by the Advanced Cruise-Assist Highway System Research Association (AHSRA). The distribution of the response time after which the driver recognizes the obstacles, the distribution of the brake operation response time and the distribution of the deceleration were obtained from experiments using a driving simulator.
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A. Hosaka, H. Mizutani

Simulator, the distribution of the danger perception speed was calculated from statistical data on accidents and, by combining these, the correlation between the time taken to reach the obstacles and the probability of avoiding an accident was calculated\(^1\). This figure shows that the probability of avoiding an accident when obstacles are discovered 3.5 seconds ahead is about 70%. If the obstacles are discovered 2 seconds earlier, this probability is virtually 100%. In the above case, an automobile alone cannot have an unobstructed view 3.5 seconds ahead. However, by installing sensors in the infrastructure along the curve, by detecting stopped vehicles or other obstacles and by informing the drivers of the vehicles by road-vehicle communication, it is possible to detect faraway obstacles which cannot be detected by automobiles alone.

Next, the effects of the road surface conditions are examined. In the case shown in Figure 1, the degree of danger increases when the surface of a curved road is slippery. Road surface friction coefficient is the ratio of the upper limit of the deceleration which can be generated by the vehicle to the gravitational acceleration.

\[
\text{Braking force} = \text{Vehicle weight} \times \left(\frac{\text{deceleration}}{\text{gravitational acceleration}}\right)
\]

Deceleration/gravitational acceleration = Braking force/vehicle weight

\[
\text{Maximum deceleration/gravitational acceleration} = \frac{\text{Maximum braking force}}{\text{vehicle weight}}
\]

\[
\text{Maximum braking force} = \text{Road surface friction coefficient} \times \text{vehicle weight}
\]

\[
\text{Maximum deceleration/gravitational acceleration} = \frac{\text{Road surface friction coefficient}}{\text{Road surface friction coefficient}}
\]

With the case shown in Figure 1, it is made possible for the driver to perceive the obstacle 50 meters ahead. If it is assumed that the response time taken to start deceleration after the obstacle has been discovered and the danger judged is 2.0 seconds established by road design and other standards, the automobile will travel 27.8 meters during this time. Consequently, the vehicle will collide with the obstacle unless it decelerates and stops in the remaining 22.2 meters. The deceleration required to do this is approximately 0.44G. When the response time is 2.5 seconds, a deceleration of around 0.67G is required; when it is 1.5 seconds, around 0.34G is required; and when it is 1.0 second, around 0.27G is required. Figure 3 shows the correlation between the response time and necessary deceleration. The friction coefficient for different road surface conditions is as follows:

- Dry roads: 0.7 or above
- Oily roads: 0.5 to 0.7
- Roads covered with a film of water: 0.3 to 0.5
- Roads covered with snow: 0.3 to 0.1
- Iced-over roads: 0.2 or below

Among the above road surfaces, an automobile will be able to stop before colliding with an obstacle provided...
that the road is dry and the response time is about 2.5 seconds. However, if the road is slippery because, for instance, it is covered with a film of water, the automobile may end up colliding with the obstacle even with the standard response time of 2 seconds or so. If it is assumed that the road surface friction coefficient is 0.2, then a stopping distance of 49 meters and a response time of nearly zero will be required. In actual fact, avoiding an accident under these conditions is impossible. However, if the infrastructure sensors detect the obstacle and the road surface conditions and the driver is informed of the conditions at least 3 seconds ahead of the obstacle (and another 3 seconds (approx. 42 meters) from the obstacle 50 meters ahead, making a total of 92 meters ahead), most drivers will be able to slow down and avoid a collision. Automobiles cannot detect the road surface conditions even several dozens of meters ahead but this is something which can be done by infrastructure-based systems.

3.3 Allocation of the roles of on-board systems and infrastructure-based systems

To summarize the above observations, it can be said that, as shown in Table 2, on-board systems are suited to taking reflective action to deal with short-distance and short-term events while infrastructure-based systems are suited to taking conceptual action to deal with long-distance and long-term events and providing support for blind spots and events in adverse environments.

In terms of traffic safety, it is desirable for reflective driving support to be covered mainly by automobiles and for the road infrastructure to support driving in blind spots and in adverse environments. In short, the automobile detects the environment around it and makes judgments on the dangers present to support the driver. The road infrastructure supports the automobile by detecting the kinds of dangers posed by environments, such as curves and intersections, which are difficult for automobiles to recognize directly. It is also necessary to make it easier for automobiles to recognize obstacles which are hard to see in rainy, foggy or snowy conditions as well, lane markings, slippery road surface conditions, etc. It is possible for obstacles to be recognized from automobiles under adverse weather conditions by means of milliwave radar or other devices but it is hard for automobiles to recognize lane markings, lanes ahead and slippery road surface conditions. Road infrastructure, on the other hand, provides effective support for this. It is therefore desirable for the functions to be appropriately allocated between automobiles and road infrastructure.

### 3.3 Allocation of the roles of on-board systems and infrastructure-based systems

<table>
<thead>
<tr>
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<th>Reflective driving support</th>
<th>Conceptual driving support</th>
<th>Support for driving with blind spots and in adverse environments</th>
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<tbody>
<tr>
<td>On-board systems</td>
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<td>Infrastructure-based systems</td>
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4.1 Basic concept

The basic concept of the Road-Vehicle Cooperative Smart Cruise System is for automobiles and road infrastructure that have been given intelligent capabilities to cooperate through road-to-vehicle communications in order to support drivers in operating their vehicles. On the basis of this concept, the Smart Cruise System was developed. This is a system to support driver operations by a collaboration between the intelligent road infrastructure system known as the Advanced Cruise-Assist Highway Systems (AHS) and the intelligent automobile known as the Advanced Safety Vehicle (ASV). The Smart Cruise System allocates road-vehicle functions according to the scheme explained in the previous chapter. Information on whatever is within the vehicle’s own range of visibility is collected by the vehicle itself. The infrastructure detects and provides information on obstacles at curves and intersections, road surface conditions in the distance, and other such data that are not easily gathered from vehicles themselves. The vehicle information processing system takes vehicle status information on speed and so on into account in determining the content of support and then providing it to the driver. The basic configuration of this system is shown in Figure 4. There are sensors to detect vehicles, pedestrians, obstacles, and so on, lane markers, road surface condition information sensors, roadside information processors, and road-to-vehicle communica-
tions devices installed on the roadside. On the vehicle side, there are road-to-vehicle communications devices, on-board sensors, on-board information processors, actuators, driver interface, and so on. The content of driver support has three levels: information, warning, and operational support. The basic functions of the driver with regard to driving are recognition, judgment, and operation. The Smart Cruise System supports these basic functions. When an error in recognition takes place that causes a delay in recognition, the system provides information that, for example, indicates the presence of an obstacle. When an error in judgment results in appropriate action such as deceleration not being taken, the system generates a warning. When appropriate action is still not taken, the system executes operational support such as emergency deceleration. The levels and the timing of support are defined with a view to keeping this support from becoming excessive intervention. The services are intended to be at a realistic level for the traffic environment, so that the system does not grow out of proportion from either the social or technological perspective. These ideas and approaches have been organized in drafts of Smart Cruise System requirements that are being further improved on the basis of comments from interested parties.

4.2 Priority systems

The services envisioned for the Road-Vehicle Cooperative Smart Cruise System are shown in Figure 5. These are intended to improve safety, efficiency, and so on. Support is provided in real time, from immediately before the phenomenon in question takes place to immediately after it. The support is directed to the basic behavior of the driver: longitudinal behavior, lateral behavior, and intersection behavior. The system of basic user services that carry out this support are shown here. Every one of these services is important individually, and since traffic safety is such an urgent issue for the entire country, it is necessary to accelerate the development of safety-related services. Ten of the basic user services are defined as safety-related. Judging from the large number of accidents involved with the functions that certain services are intended to provide, these services have been assigned priority for development. The seven services judged to be vital and urgent are: support for prevention of collisions with forward obstacles, support for prevention of over shooting on curves, support for prevention of lane departure, support for prevention of crossing collisions, support for prevention of right turn collisions, support for prevention of collisions with pedestrians crossing streets, and support for road surface condition information for maintaining headway etc. These services address the causes of more than 90% of traffic accidents involving death and injury. A conceptual image of the services in question is provided in Figure 6.

4.3 Examples of system operation

Here those basic operations will be explained, taking the support for prevention of collisions with forward obstacles as an example. The basic operation that occurs when there is a stationary vehicle on a curve or other lo-
cation where visibility is limited is shown in Figure 7. The timing of the support is shown in Figure 8. The timing of these items will vary according to vehicle speed, deceleration rate (which depends on vehicle performance and road surface condition), and driver response time. The infrastructure sensors detect the stationary vehicle in the road ahead that cannot be detected from the cruising vehicle. This information is passed to that vehicle through
road-to-vehicle communications. The vehicle calculates a deceleration time that will allow it to stop without colliding with the obstacle when deceleration takes place within the driver’s reaction time and at a normal rate that does not decelerate too rapidly. It then provides the driver with information that is timed to assure that deceleration can take place within the specified time. If the driver responds to that information with the appropriate action, such as deceleration, then the role of the system is over. However, if the driver continues to approach the obstacle without showing any sign of reacting to the information provided, then the system provides a warning that is timed to the driver’s reaction time and a period of deceleration that assures that the driver can stop the vehicle and avoid a collision with the obstacle by decelerating rapidly. If the driver still does not take appropriate action, then the system executes deceleration control that is timed to allow the vehicle to be stopped and so avoid collision with the obstacle by decelerating the vehicle within the reaction time of the system and its capability for emergency deceleration.

Here, the effects that are to be anticipated from the Road-Vehicle Cooperative Smart Cruise System will be explained. The priority services explained above cover 90% of the traffic accidents that occur. The Smart Cruise System is intended to address 75% of the human factors that cause those accidents. The results of surveys conducted by the Advanced Cruise-Assist Highway System Research Association (AHSRA) show that each service has a 0.75 effectiveness rate. Multiplying these together produces a rate of approximately 0.5. This means that accidents can be reduced by approximately half if the system is installed on all vehicles, the infrastructure is 100% in place, and all the services are utilized. Various environmental conditions and technical restrictions sometimes make it difficult to utilize the system fully in all traffic environments. In addition, attempting to extend system coverage up to reckless driving speeds would require the use of extremely high-performance systems. Operations such as right turns at intersections involve a variety of judgmental factors, and it is currently difficult to provide support that would surpass the judgment of the driver. Given these considerations, there has been no choice but to focus realistically on the technology and scope of application for the system as it will actually be deployed. The resulting accident reduction is estimated as approximately 20%, which means that the system will have an impact on approximately 40% of accidents in all.

In order to achieve a dramatic improvement in traffic safety, drivers, vehicles, and road infrastructure must be made increasingly sophisticated and intelligent. There are limits, however, on measures for separate application in each area, so there is the need for a support system that links together vehicles and road infrastructure. Research and development work on the Road-Vehicle Cooperative Smart Cruise System has been carried out from this perspective. The system supports the basic driver functions of recognition, judgment, and operation, and is intended to support accident prevention by covering the human errors that form the majority of traffic accident causes. Development and application of this system in an ideal manner would allow a significant reduction in traffic accidents. At present, development is proceeding on the Road-Vehicle Cooperative Smart Cruise System that links together the ASV, which is being promoted by the Ministry of Transport, and the AHS, which is being promoted by the Ministry of Construction. Proving tests of the Smart Cruise System are planned to take place between Oct. to Dec. 2000. These proving tests will serve to verify system functions, evaluate their effectiveness, evaluate their acceptability to drivers, and so on. If the results of the proving tests show that the system is effective, a program will thereafter be put into effect to promote the study of related issues and measures in order to work toward practical application of the system. We anticipate early realization of the Road-Vehicle Cooperative Smart Cruise System and attendant dramatic improvements in traffic safety.