TRAFFIC MANAGEMENT SYSTEM AGAINST MAJOR EARTHQUAKES

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This paper describes fundamental issues of the traffic management systems and the actual traffic conditions following the Hanshin-Awaji Earthquake. Based on these issues, a new concept of traffic management system against an earthquake disaster is proposed, and the effectiveness of 2-stage area traffic regulation is examined through the case study for accommodation of personal passenger car demand immediately after the earthquake.Additionally an integrated traffic management system against a major earthquake and the related issues are discussed. It is expected that ITS technology will play an important role in the future development of traffic management system during an earthquake disaster.

Key Words: Emergency traffic management system, Traffic condition following earthquake, Personal passenger car use, 2-stage area regulation, ITS application

1. INTRODUCTION

The near-field ground motion caused by the Great Hanshin-Awaji Earthquake of January 17, 1995 devastated the transportation network of the stricken area, and left the urban infrastructure paralyzed. The road network itself suffered the destruction of expressways and bridges as well as the blocking of major arteries, resulting in the closure of road traffic and traffic jams, which caused serious difficulty with travel not only for ordinary cars but also for emergency vehicles. Despite the nearly total confusion, the role of the automobile in both rescue and emergency aid activities as well as in the later restoration and redevelopment of the damaged area was very important, and demonstrated the necessity for the development of a traffic management system that can maintain a level of road network functionality as highly as possible even when partially disabled by events such as earthquakes or other disasters.

It should be noted that a traffic management system against an earthquake must be able to respond adequately to changing traffic conditions across time. Accordingly, the traffic management system requires countermeasures before and after a major earthquake, which consist of both the construction and maintenance of physical infrastructures as well as the implementation of a system operation. The remarkable advances made in recent years in the development of ITS (Intelligent Transport Systems) have shown that an advanced traffic management system capable of managing a damaged traffic network is now at a stage for practical use.

In this paper, Chapter 2 focuses on issues related to traffic management systems that were exposed by the Great Hanshin-Awaji Earthquake, and Chapter 3 shows the actual traffic conditions after the huge earthquake. Chapter 4 proposes a basic concept for a new traffic regulation method after earthquakes based on the aforementioned issues. Chapter 5 shows also a case study for the area affected by the Hanshin-Awaji Earthquake presenting estimates of traffic volume generated by the use of privately owned automobiles during the first 72 hours after the earthquake, and demonstrates the effectiveness of two-stage area regulation. Finally, Chapter 6 discusses issues related to the integration of traffic management systems against a major earthquake and issues on the future research subjects.

2. FUNDAMENTAL ISSUES ON TRAFFIC MANAGEMENT IN THE EVENT OF EARTHQUAKE DISASTER

As traffic was in absolute chaos following the earthquake due to extensive damage over a wide range of railway, road and harbor facilities, the question is often asked as to why authorities were unable to effect more efficient traffic management. If the problem is limited simply to the road traffic system, although traffic management systems for the control of traffic flow have made remarkable advances through developments such as advanced traffic signal control systems, these systems are mainly configured to operate under ordinary circumstances, and are unable to respond well to the conditions that arise following a major earthquake. We are still a long way away from the implementation of a comprehensive traffic management system capable of coordinating both road traffic and public transportation systems following major earthquakes. A number of issues related to traffic jams generated by a major earthquake and the inability of our present traffic management systems to function under such conditions were revealed during this experience. Or, to put it another way, finding solutions to the problems revealed by the Great Hanshin-Awaji Earthquake will lead to helping us develop traffic management systems that operate following earthquakes. These issues and problems are summarized below.

(1) Lack of data collection system for damaged condition of traffic facilities

There has been no efficient system for the collection of information about damage to transportation facilities. In implementing traffic management following an earthquake, accurate and up-to-date information regarding damage is essential in order to identify the level at which damaged facilities can continue to handle traffic flow. The longer it takes to determine the extent of damage, obviously, the longer it will take to implement countermeasures to deal with this damage, which in turn could contribute to the spread of secondary damage due to fire, etc. Serious consideration should be given to centralized processing of information about damage for the implementation of comprehensive traffic management.

(2) Insufficiency of past studies on travel behavior characteristics during earthquake disasters

There are numerous unidentified effects of natural disasters on traffic conditions. The accurate and effective management of traffic requires that as many traffic condition characteristics as possible be identified. Little is known, however, about how the onset of a natural disaster affects traffic behavior characteristics. The outbreak of a natural disaster affects every travel behavior, such as destination choice, frequency of travel, route and mode choices, thereby creating traffic patterns that differ greatly from ordinary ones. The use of automobiles for travel after an earthquake differs greatly from such use before, and travel by emergency vehicles in both rescue and emergency aid activities is a special feature not seen under normal conditions.

(3) Difficulty with traffic data collection after an earthquake

The collection of traffic data after a natural disaster is extremely difficult. Traffic phenomena are extremely transient in nature, yet because of the state of confusion that exists after a natural disaster, collecting traffic data is generally not an immediate priority. Traffic detectors installed along roads to collect data can also be affected by the disaster, and become unable to gather accurate data. Onsite surveys which take place some days after the disaster are able to provide an idea of how traffic patterns have changed after things have settled down, but it is extremely difficult to obtain accurate and detailed information about traffic during the time of confusion immediately following the disaster. In order to solve this problem, it will be necessary to develop highly advanced traffic data collection systems in normal situations.

(4) Lack of comprehensive traffic management system

There is no unified system for the comprehensive management of all modes of transportation systems. At present, traffic management systems for railways and roads are entirely independent of each other. This is not a problem in instances where there is relatively little damage, but when damage is spread across a wide area after an earthquake, it becomes difficult to manage the confusion in just a single transport mode.

(5) Necessity for a traffic management system responsive to changing damaged conditions

Traffic management systems must be able to respond adequately to changing conditions across time during unexpected disasters. It is difficult to predict just what shape natural disasters will take. Furthermore, disaster conditions will change as time proceeds. Ordinary traffic management is based on handling relatively stable traffic conditions, and in general is based on static models of traffic flow. Management of traffic conditions that occur after natural disasters, however, are exceedingly complex, and must be based on dynamic models, requiring extensive calculations.

(6) Shortage of hierarchical structure of transportation networks

At present, most transportation networks lack the structure for stratification, substitutability, and mode-connectivity. It is desirable for road networks to have a rational hierarchy of main trunk roads, supplementary trunk roads and district roads. There are numerous benefits both in efficiency and safety to managing roads so that intercity traffic travels on main trunk roads, intra-city traffic on supplementary trunk roads, and local traffic on district roads. This type of stratified road network enables the easy implementation of traffic regulations based on the road's importance as an emergency road and traffic use characteristics.

A road network with a hierarchical structure must provide alternative routes. The availability of alternative routes is considered crucial to a road network's redundancy and reliability. A transportation network must also offer easy interchangeability between transportation modes such as road, railway and harbor facilities. It is difficult to manage transportation following a natural disaster with just a single transport mode, and the availability of alternative transport modes permits the flexible utilization of a variety of approaches after natural disasters.

(7) Insufficiency of contingency plans against earthquakes

There were insufficient contingency plans such as the designation and set up of emergency roads, emergency relief centers and evacuation centers. It is necessary to designate emergency roads in advance, which are to serve as the basic routes for the transport of rescue and emergency vehicles and emergency supplies. The reason for this is that it is necessary to educate the public on an ongoing basis as to which routes are designated for emergency use so that they will know which roads are to be used for which purposes during emergencies. It is also necessary to repair or otherwise add roads that form these emergency routes in the event that they are damaged during the disaster, thereby mitigating confusion during emergencies. The same can be said of emergency supply bases and evacuation areas, which are highly dependent on the availability of the transportation network to achieve their function.

The location and extent of a natural disaster will affect the distribution of evacuation centers, and the extent of damage to roads will affect the manner in which emergency logistics centers are utilized. By developing contingency plans regarding the basic location of a variety of emergency facilities, it becomes possible to configure quickly a road network system capable of responding to varying circumstances.

3. ACTUAL ROAD TRAFFIC CONDITIONS AFTER THE GREAT HANSHIN-AWAJI EARTHQUAKE

In order to configure a road transport system for use after a major earthquake, it is necessary to understand how traffic conditions are impacted by such an event. Let us show some striking data of the traffic conditions that occurred after the Great Hanshin-Awaji Earthquake.

Damage from the earthquake rendered two expressways as well as the JR West, Hankyu and Hanshin railways impassable, putting transportation between the cities of Osaka and Kobe into total confusion. Under ordinary conditions, 200,000 vehicles per 12 hours travel over National Routes 2 and 43, as well as the Kobe and Harbor routes of the Hanshin Expressway. The Kobe line of the Hanshin Expressway, however, is an elevated highway running directly above Route 43, and when a section of this highway collapsed during the earthquake, both of these roads were blocked to traffic. When the damaged Harbor route was closed as well, Route 2, which with a capacity of only 30,000 vehicles per 12 hours would ordinarily deal with only 15% of the overall traffic volume, was left as the only route connecting Osaka and Kobe after the earthquake.

Furthermore, the three railway lines which were used daily by 650,000 passengers were closed completely, leaving Kobe's transportation system at less than 5% of its normal capacity. This situation alone is enough to demonstrate the severity of the earthquake's impact on traffic conditions in Kobe[1].

Figure 1 represents the hourly traffic volume for west-bound vehicles traveling on Route 2 between Mikage and Tanaka as observed during three-day periods directly after, one week after, three weeks after, and seven weeks after the earthquake. In order to compare these traffic movements with those for ordinary time, traffic volume data for 1994 are represented as unity. As can be seen, daytime traffic dropped directly after the earthquake, and then gradually returned to prior levels three weeks later. In contrast, nighttime traffic increased dramatically after the earthquake, and continued to maintain that level almost two months later. The reason for this was that with Route 2 the only passable highway, traffic that could not travel during the daytime hours had to wait until nighttime to complete its travel. Even on Sundays, by the way, in which under ordinary conditions there would be more traffic during the day than during the night, nighttime traffic

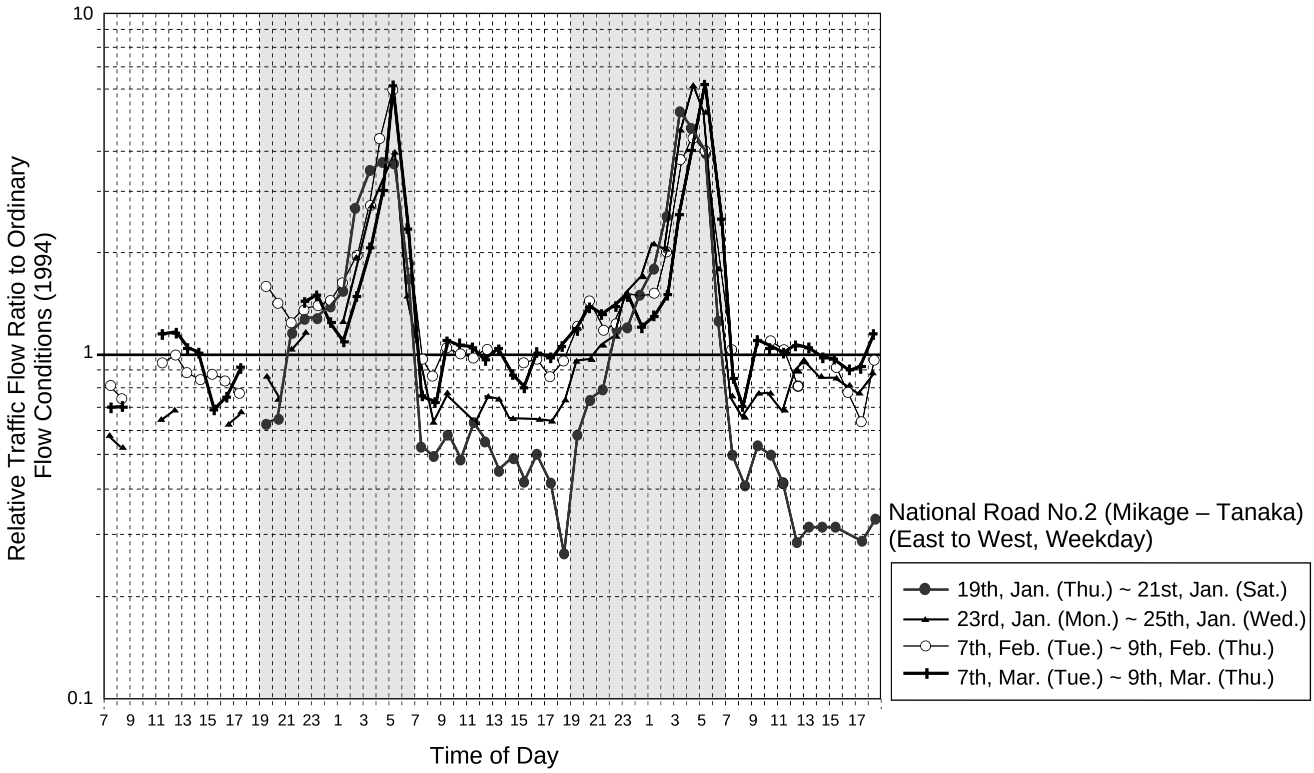

Fig. 1 Variation in hourly traffic flow pattern after earthquake

volumes were observed to exceed daytime traffic volumes after the earthquake. An estimate of weekday OD traffic volume (or traffic flow between Origin and Destination nodes) based on observed link volumes is shown in Figure 2, which is generated in the areas of Kobe affected by the earthquake[2]. Prior to the earthquake, there were approximately 50,000 trips per day, which immediately after the earthquake dropped to 35,000 vehicles, or 70% of the former level. This result also shows a gradual recovery to former levels as time proceeds.

Based on the above data, traffic conditions in Kobe following the Great Hanshin-Awaji Earthquake can be classified as follows: For three days to one week following the earthquake can be characterized as "a state of confu-

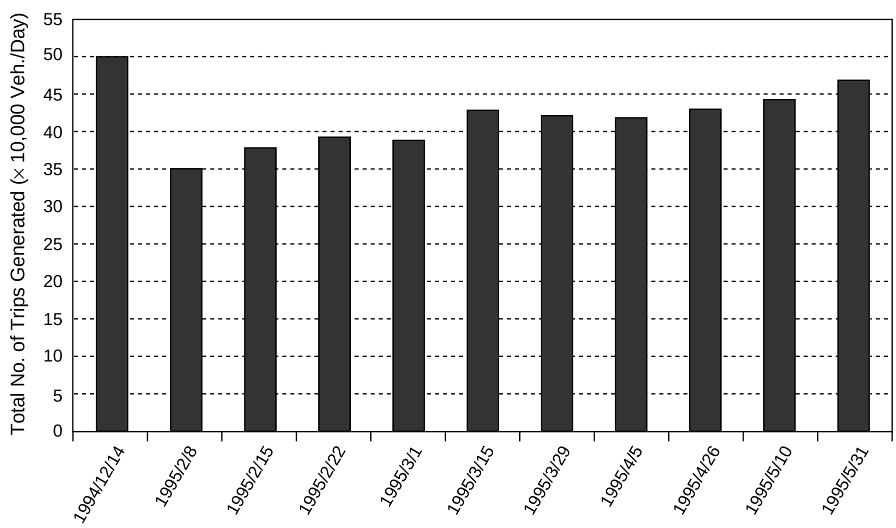

Fig. 2 Estimates of the total number of trips generated in the study area

sion", in which traffic volumes drop sharply with extreme congestion during the daytime followed by an increased traffic volume at night. Sometime from the first week following the earthquake to the third week, "a state of settlement" begins, wherein daytime traffic levels begin to return gradually to their former levels, and differences between daytime and nighttime traffic return to more ordinary patterns, and traffic on Sundays and holidays continues to increase. The period of one month after the earthquake is "a state of stability", wherein daytime traffic volumes throughout the week return to former levels in spite of the fact that nighttime traffic volume continues to be heavy.

4. TRAFFIC MANAGEMENT SYSTEM AFTER A MAJOR EARTHQUAKE

4.1 Basic concepts of emergency traffic management

Methods of traffic regulation vary with traffic conditions, and it is important to be able to grasp the dynamic behavior of traffic across time not only in the regulated areas but also throughout the road network as a whole. Because of the importance of emergency rescue and relief activities during the period of confusion directly after the disaster, emergency vehicles traveling along roads that have been designated for emergency use must be given priority of passage, and the passage of ordinary passenger vehicles must be fundamentally limited even along routes not specifically designated for emergency travel. Approximately one week after the disaster, traffic from vehicles involved in emergency relief and restoration activities will increase, and as the overall traffic conditions settle, traffic regulations that ensure the use of roads for emergency recovery traffic must be given priority. Approximately one month after a disaster, traffic conditions stabilize, and as restoration work begins in earnest, traffic regulations that facilitate the flow of traffic related to restoration work should be implemented. About this same time, the daily activities and lifestyle begins to return to normal, and the transport of materials necessary for this must also be considered. An image of traffic regulations after a major natural disaster is shown in Figure 3[3].

Let us make some comments about time-based traffic regulations from the perspective of road traffic conditions. With regard to time-based traffic regulations, insofar as traffic dynamics will be in a state of confusion immediately after natural disasters, frequent modification of regulations could tend to exacerbate rather than mitigate problems, and limiting time-based traffic regulations to daytime vs. nighttime as well as weekdays vs. weekends and holidays type of configuration is a practical approach. For example, nighttime traffic on Route 2, which had been designated an emergency transport route, remained very heavy even three weeks after the earthquake. If the nighttime traffic volume had been sparse relative to the daytime traffic volume, it would have been possible to lift restrictions imposed by the designation as an emergency transport route, but under conditions where there was no appreciable difference between daytime and nighttime traffic, there was a tremendous traffic demand for an emergency route, and 24-hour-a-day regulations were unavoidable. If the nighttime traffic volume had fallen appreciably, resulting in sufficient road network capacity, it would have been possible to augment the short-

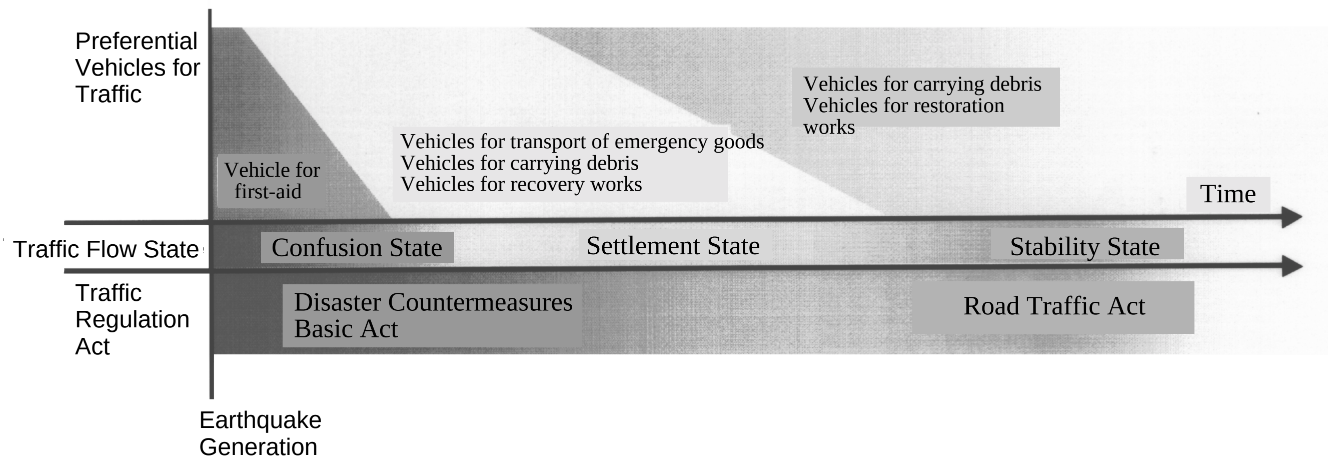

Fig. 3 Image of traffic regulation after an earthquake disaster

age of capacity for passenger traffic during the daytime by relaxing emergency road traffic regulations at night.

Traffic regulations based on the day of the week are as follows: Daytime traffic volume on Sundays increases until approximately one month after the earthquake, after which it decreases slightly. One particularly noticeable characteristic is that daytime traffic volumes on Sundays are significantly higher than the weekly average for daytime traffic volume. In contrast to this, nighttime traffic volume on Sundays exceeds daytime traffic volume, a condition that continued even three months after the earthquake. The difference between nighttime traffic volume on Sundays and the weekly average nighttime traffic volume is even greater than that for daytime traffic volume, indicating that the traffic demand volume for both daytime and nighttime on Sundays is appreciably larger than for other weekdays, and the implementation of traffic regulations designed to ensure the passage of emergency transport throughout the entire day can be considered appropriate.

Analysis of changes in OD traffic volume for automobiles within road networks of the Hanshin region after the earthquake has revealed the following[2]: The OD ratio of short-distance trips increased greatly. The OD ratio of long-distance trips, particularly trips which originate outside of the affected area but which would ordinarily pass through it, decreased. The OD ratio of trips originating inside the Hanshin region to areas outside decreased. The OD ratio of trips originating outside the Hanshin region to areas inside increased greatly.

Of these phenomena, the one with the most relevance to traffic regulation is the increase in the OD ratio of short-distance trips. This increase can be seen as being directly related to activities such as the verification of the safety of relatives or acquaintances, the purchase of goods and materials, and the evacuation of victims, and is generated in large part by the need to rely on automobiles due to a lack of availability of other modes of transportation normally used for everyday activities. This indicates the desirability of traffic regulation that affects short-distance trips as little as possible. This requires that traffic that would ordinarily pass through the area affected by a natural disaster by rerouted to roads that are far away from the regulated area. If through-traffic is rerouted away from the regulated area, much more traffic capacity becomes available for use for traffic within the affected area. There is a limit, however, to the effectiveness of diverting through-traffic, and in order to handle traffic generated by short-distance trips within the affected area, long term planning of a road network construction with a hierarchical structure with sufficient trunk road capacity is necessary. The increase in the OD ratio of trips originating outside the Hanshin region to areas inside is thought to be generated by emergency relief and restoration activities and the basic concept for the managing of this traffic is that it be guided to the designated emergency routes.

4.2 Area traffic regulation

Area regulation was newly introduced with revisions to the Disaster Countermeasures Basic Act with the intention of facilitating emergency rescue and relief activities as well as mitigating the spread of damage in response to on-site conditions, and accommodates the enactment of traffic regulation not just within the affected area, but in conjunction with unified regulation of traffic in surrounding areas.

Area regulation refers not to linear regulation of traffic within specific segments or routes of roads, but rather to the overall regulation of traffic within a particular area. In the aftermath of the Great Hanshin-Awaji Earthquake, there were a number of areas in which rubble from houses, buildings, and even telephone poles and walls blocked roads, paralyzing traffic in entire area-blocks. There were also areas where the removal of such rubble as well as the restoration of life-line services such as electricity, water and gas required the prohibition of ordinary vehicular traffic. These areas require regulation of all traffic but emergency vehicles, and the need is apparent for the development of contingency plans delineating the scope and method of implementation.

The implementation of area regulation can be undertaken by a traffic management system based on a network capacity model[4]. Through the use of a network capacity model, estimates can be made of maximum values for generation and concentration traffic volumes within each zone or area-block, given decreased (or damaged) road link capacities. By comparing the values obtained from this model with those for generation and concentration traffic volumes under ordinary conditions, calculations can be made of the extent to which traffic in each zone must be regulated.

Concrete methods for the implementation of area regulation require a planning of dividing the area to be regulated into zones or area-blocks before earthquake. It would be extremely difficult to designate zones for area regulation during the state of confusion directly after the outbreak of an earthquake disaster. As shown in Figure 4, for instance, designation of main trunk roads and supplementary trunk roads as the borders of a minimum size unit of area-blocks would make it relatively easy to

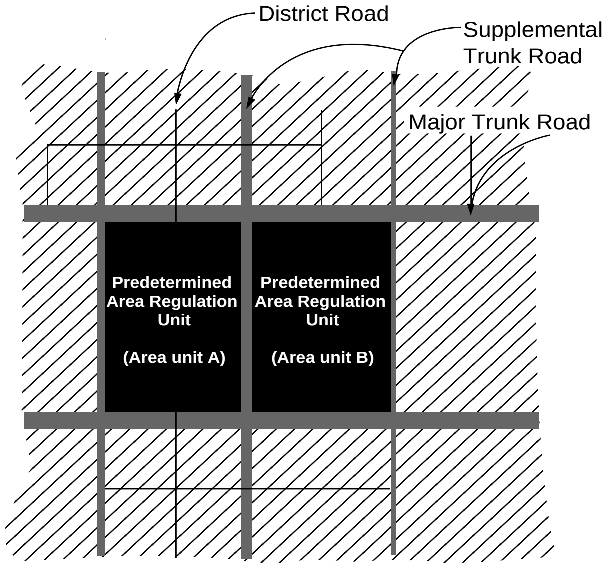

Fig. 4 Example of area regulation unit

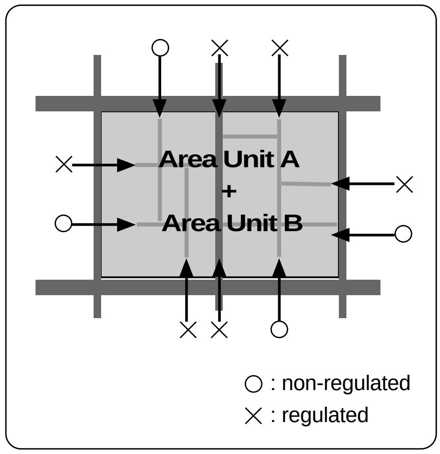

Fig. 5 Example of area regulation

reorganize adjacent unit areas into blocks of larger unit areas as necessary depending on the damage condition. The use of a ward-size or a city-size block as the smallest unit of division is also an effective way to implement traffic regulation, depending on the damage condition of the road network. Area regulation for limiting the number of vehicles allowed to enter a regulated zone can be effected by allowing only vehicles with valid permits to enter. An example of this type of area regulation is shown in Figure 5.

5. CASE STUDY OF TRAFFIC MANAGEMENT BY 2-STAGE AREA REGULATION

5.1 Traffic management system immediately after an earthquake

There are a variety of approaches available for the implementation area traffic regulation. Once main trunk roads and supplemental trunk roads are designated as the border of the small zones or blocks subject to regulation, it becomes necessary to implement a fairly detailed policy of traffic regulation or guidance. For example, the volume of traffic allowed to enter a particular block must be regulated by a percentage equivalent to the reduction in road network capacity caused by the disaster; or the traffic volume generated in each block must be held below a certain level through regulation or guidance. In the future, as the development and implementation of ITS technology progresses, this type of traffic regulation system will undoubtedly be in effect in an ordinary situation. In the aftermath of a natural disaster, however, there will be limits to how well this type of area traffic regulation can be implemented on such a detailed scale, and in order for this system to function effectively, traffic conditions must be rather well settled. Therefore, in situations where traffic conditions are in a state of confusion, it is more pragmatic to use city-wide or district-wide implementation of traffic regulation, and the content of the regulation as well is better if limited to a simple, easy-to-understand format such as limiting entry to emergency vehicles or vehicles with permits only.

Another important factor in the management of traffic after a major earthquake is the approach taken in the handling of ordinary vehicular traffic, especially of privately owned passenger cars. The extensive use of privately owned passenger cars not only for evacuation or the procurement of supplies, but also for confirming the personal safety of relatives or acquaintances has been revealed by the results of a survey of passenger car use in the aftermath of the earthquake[5]. Not only does this make the absolute prohibition of passenger cars highly problematic, but in consideration of the fact that most of these trips were for very short distances, it argues for a policy that permits their use as much as possible.

5.2 Concept and model structure of 2-stage area regulation

One possible scheme for 2-stage area regulation is shown in Figure 6. The areas shown are those most severely damaged by the earthquake, including the cities of Nishinomiya and Ashiya as well as the Higashi-Nada, Nada, Chuo, Hyogo, Nagata and Suma Wards of Kobe.

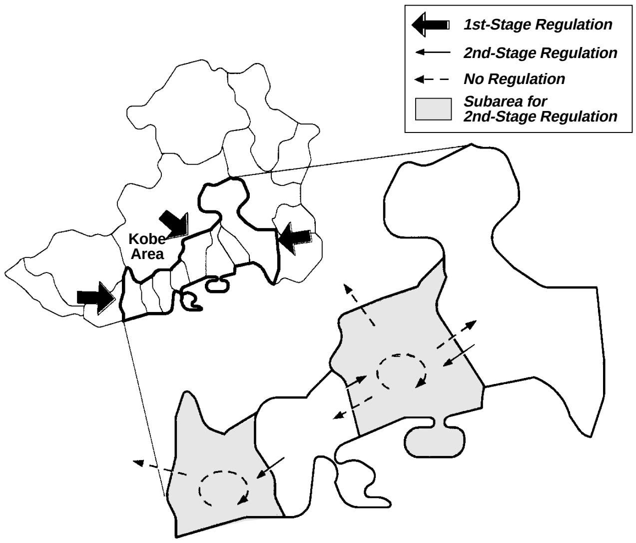

Fig. 6 Image of 2-stage area regulation

The 1st stage regulation in this scheme involves the complete prohibition of the entry of vehicular traffic from regions outside the damaged area except for emergency vehicles. The 2nd stage regulation executes the designation of the areas stated above as regulation sub-areas, and the prohibition of the entry of traffic into these sub-areas. Under the 2nd stage area regulation, traffic could move freely both within the sub-areas themselves and out of the sub-areas to unregulated areas.

The effect of the implementation of 2-stage area regulation will vary depending on factors such as the driver's route choice behavior or the extent to which dynamic route guidance information is provided, but for simplicity, let us assume that drivers select the shortest route in terms of travel time. Assuming that the traffic manager is able to effect complete control of traffic with both the 1st and the 2nd stage area regulation, then the 2-stage area traffic regulation model can be formulated as shown below[5].

Upper Problem

$$\theta\sum_{i\in\mathbf{N}}\sum_{j\in\mathbf{N}}\xi_{ij}OD_{ij}+\phi\sum_{i\in\mathbf{N}}\sum_{j\in\mathbf{N}}\eta_{ij}OD_{ij}+\sum_{i\in\mathbf{N}}\sum_{j\in\mathbf{N}}(1-\xi_{ij}-\eta_{ij})OD_{ij}\rightarrow \max$$

subject to

$$0\le\theta,\ \phi\le 1$$
$$X_a\le \mu C_a \text{ for all } a\in \mathbf{L}$$

Lower Problem

$$\sum_a\int_0^{x_a} t_a(x)dx\rightarrow \min$$

subject to

$$\sum_{k\in\mathbf{K}_{ij}}h_{kij}=\theta\xi_{ij}OD_{ij}+\phi\eta_{ij}OD_{ij}+(1-\xi_{ij}-\eta_{ij})OD_{ij} \text{ for all } i\in\mathbf{N}, j\in\mathbf{N}$$

$$X_a=\sum_{i\in\mathbf{N}}\sum_{j\in\mathbf{N}}\sum_{k\in\mathbf{K}_{ij}}\delta_{akij}h_{kij} \text{ for all } a\in\mathbf{L}$$

$$h_{kij}\ge 0 \text{ for all } k\in\mathbf{K}_{ij},\ i\in \mathbf{N}, j\in \mathbf{N}$$

where

θ : entry permission rate for 1st regulation
ϕ : entry permission rate for 2nd regulation
ξ_{ij} : if OD pair *ij* is involved with 1st regulation, then 1, and otherwise 0
η_{ij} : if OD pair *ij* is involved with 2nd regulation, then 1, and otherwise 0
OD_{ij} : Traffic volume between OD pair *ij*
$\mathbf{N}$: a set of centroids
$\mathbf{L}$: a set of links
$\mathbf{K}_{ij}$: a set of paths for OD pair *ij*
X_a : traffic flow on link *a*
μ : allowable congestion level
C_a : capacity flow on link *a*
$t_a(x)$: travel time function on link *a*
h_{kij} : *k*-th path flow between OD pair *ij*
δ_{akij} : if *k*-th path between OD pair *ij* is included in link *a*, then 1, and otherwise 0

5.3 Traffic demand estimates of personal passenger cars immediately after the earthquake

In order to examine the effects of 2-stage area regulation on personal passenger car traffic following an earthquake, estimates are made of personal passenger car trips for probable trip objectives, which are distributed onto the road network, and regulation percentages are calculated for each trip purpose. According to the results of a questionnaire survey of personal passenger car use during the first three days of the aftermath of the Great Hanshin-Awaji Earthquake[5], the most common objectives are “confirmation of the personal safety of relatives and acquaintances” at 32%, “commuting to work” at 25%, “evacuation” at 24%, and “to procurement of drinking water etc.” at 11%. The transport of the sick or injured is no greater than 8%. The data from both this survey and also from the 3rd Kyoto/Osaka/Kobe Person-Trip survey are then used to estimate traffic demand for commuting trips, procurement trips, personal safety verification trips and evacuation trips within the areas shown in Figure 6, subject to traffic regulation after the earthquake, the total of which is regarded as overall traffic demand of personal passenger cars for three days after the earthquake. The transport of sick or injured by personal passenger car is ignored in this study due not only to the fact that the traffic volume is unexpectedly little but also because it was not subject to regulation.

The traffic demand for commuting trips generated across the entire regulated area is estimated to be 120,000 trips, based on the generation model constructed from the survey and the person-trip data. According to the questionnaire survey, the percentage of working people who actually went to work is 60% for the first day, 80% for the second day, and 100% for the third day, and the estimation of commuting traffic demand for each day is made using these percentages. Estimated traffic demand with the percentage varying for each of the three days for other types of trip purpose are 150,000 trips for procurement, 150,000 trips for personal safety confirmation, and 60,000 trips for evacuation, which were made over the course of the three days. The results of these calculations are shown in Figure 7.

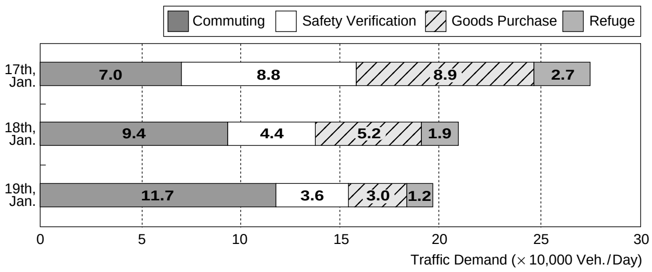

Fig. 7 Estimates of personal car traffic demand by trip purpose after earthquake generation

5.4 Case study results and discussion

Of the three days under consideration, January 17 (the day of the earthquake itself) shows the greatest demand of passenger car traffic: an estimated 270,000 trips. With this traffic demand of personal passenger cars, the 2-stage area regulation model is applied to the damaged area shown in Figure 6. The results, shown in Figure 8, indicate that the 1st stage regulation rate ($1 - \phi$) is 0.70, and the 2nd regulation rate ($1 - \theta$) 0.99. The value of the ratio for the 1st regulation implies that it would be possible to accept approximately one third of the traffic from areas outside the regulated area. In contrast, the value of the ratio for the 2nd regulation indicates that such regulation is nearly complete. Although the value of the ratio for the 1st regulation indicates that there is a certain amount of residual road network capacity, this is probably best kept in reserve to accommodate emergency vehicles from outside the regulated area, and passenger car traffic should be kept prohibited. In contrast, there is no leeway at all within the 2nd regulation, and passenger car traffic is permitted only within the sub-areas themselves. Consider-

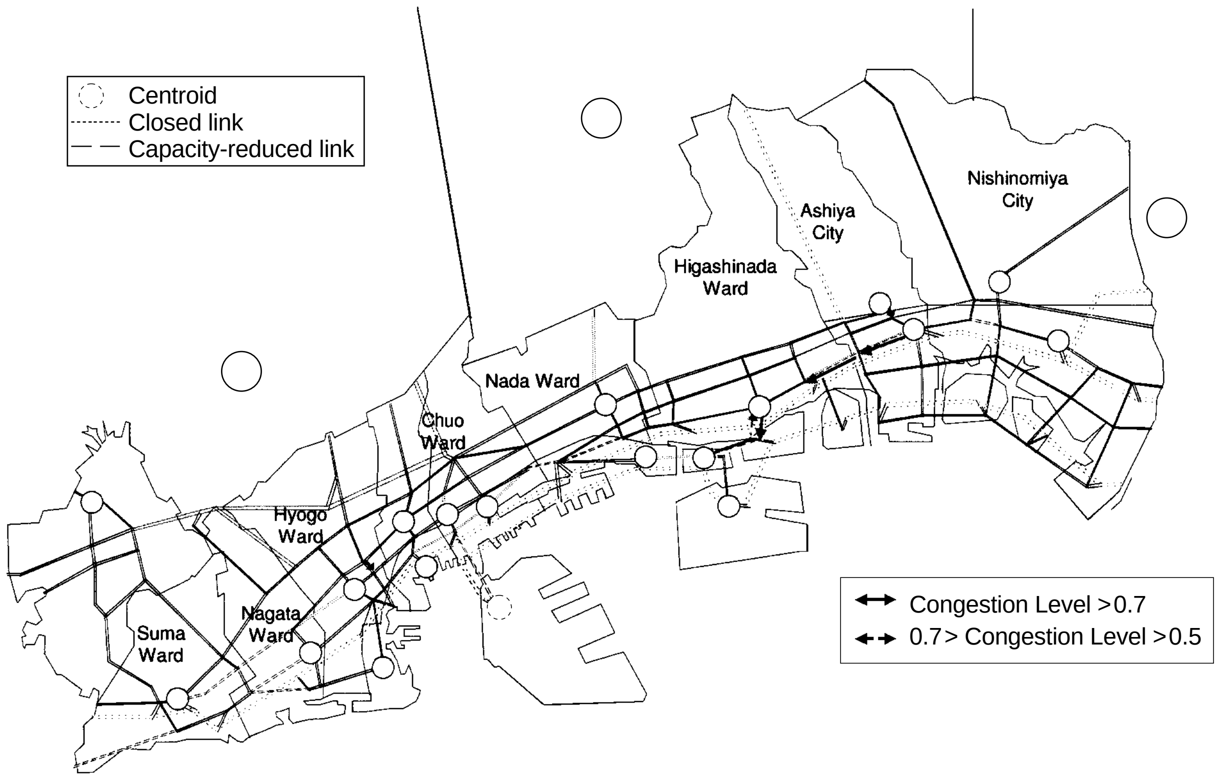

Fig. 8 Result of road network flow by 2-stage regulation model

ing that it is also necessary to ensure passage for emergency vehicles within the sub-areas, it might even be necessary to reduce passenger car traffic within the sub-areas.

When the 2-stage area regulation is implemented in this case study, the estimated percentage of unregulated passenger car trips for each trip purpose is shown in Figure 9. As evacuation trips could be accommodated at 100%, there would likely be few problems with the traffic generated by evacuation. For procurement trips, the ratio of unregulated trips would be between 50% and 70%, and for personal safety confirmation or commuting trips, about 30%. This result indicates that the 2-stage area regulation would likely cause victims of the earthquake few problems with performing trips necessary for their survival such as evacuation or procurement. It should be requested, however, to reduce trips for purposes that have low emergency priority such as commuting trips or that which could be accomplished by other methods such as personal safety confirmation trips. If industries and companies could establish a rule for commuting that release employees from obligation to commute during the period directly following an earthquake, a large percentage of the traffic demand for commuting during the critical period after the earthquake could be eliminated.

Fig. 9 Ratio of non-regulated trips by purpose

It has been known that a large portion of personal safety confirmation trips made in the wake of the Great Hanshin-Awaji Earthquake was a direct result of the inability to make contact by telephone, and the development of an emergency communications system to serve this purpose could result in a large reduction in this kind of trip. The majority of procurement trips as well, which are made to obtain food and drinking water, etc., could be eliminated by the development of emergency provision and transport systems. From this, it can be concluded that a large percentage of the passenger car traffic after

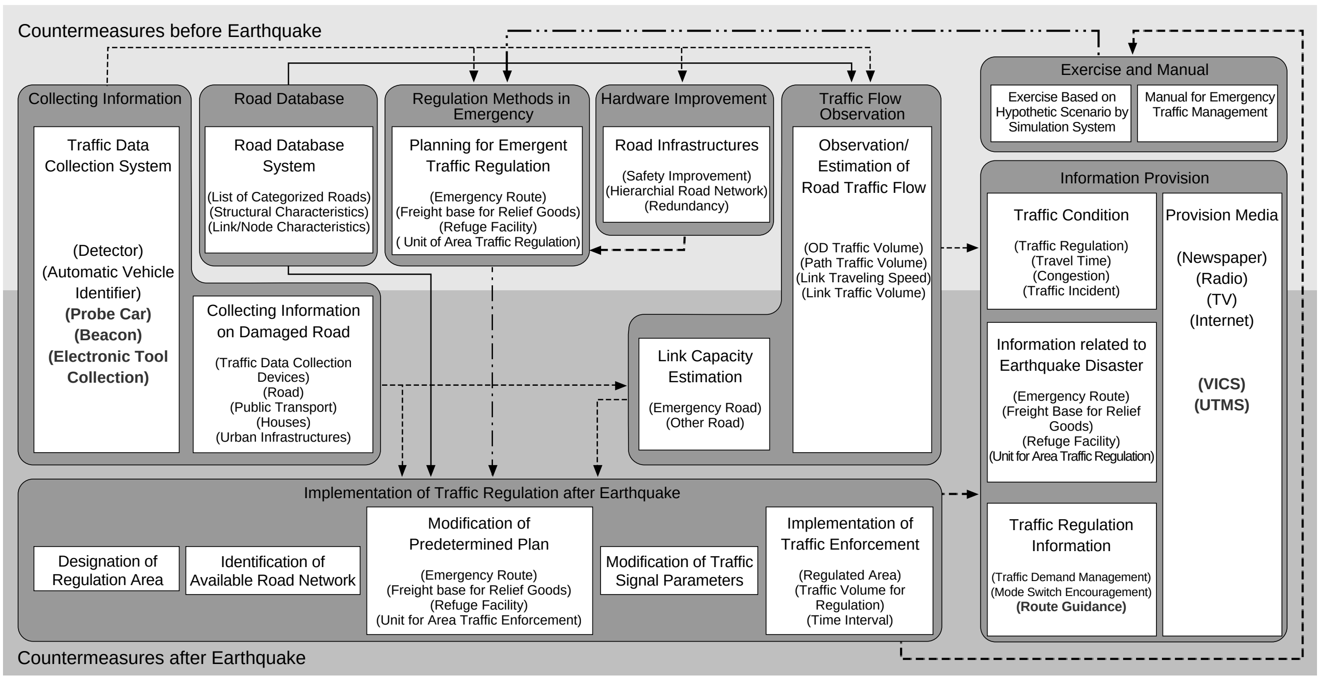

Fig. 10 Basic concept of road traffic management system against earthquake disaster

an earthquake could be eliminated, and that even with the need to permit the passage of emergency vehicles, the 2-stage area regulation is a practical solution to traffic management under these conditions.

6. INTEGRATED TRAFFIC MANAGEMENT AGAINST A MAJOR EARTHQUAKE AND RELATED ISSUES

The basic concept of a system for traffic management against a major earthquake is shown in Figure 10. In order to mitigate the reduction in road network function after such an event, it is necessary to effect a systematic approach before and after a major earthquake that incorporates both the establishment and maintenance of physical infrastructures as well as the implementation of a system of operation. One of the basic approaches to traffic management following an earthquake is to ensure that the facilities necessary for such management perform their functions in a systematic manner. It is self-evident that traffic facilities need be built to the most up-to-date specification for seismic resistance, and that a system be in place for the timely repair of whatever damage might occur. It is preferable that an integrated approach be adopted for the creation of a highly redundant (or reliable) and hierarchical road network, for such a system is resistant to large losses of capacity across the entire network. It is also important to develop the countermeasures before an earthquake that pre-designate components of the system such as emergency roads and emergency relief centers, and to establish a system for the rapid modification of the predetermined emergency routes and facilities in the event that they are damaged in order to ensure the effective implementation of emergency activities and the efficient transport of emergency supplies.

With regard to the implementation of a system for the operation of these facilities, it should be emphasized that the continuous observation and recording of traffic data during ordinary operation are extremely important. Effective traffic management is dependant on reliable traffic data not only during normal operation but also especially in the aftermath of a major earthquake. By having a system for the continuous observation of normal operation, not only can a wide variety of traffic behavior characteristics within the road network be identified, but also data becomes available to augment shortages caused by damage to detectors during the earthquake. Once a system is constructed for the analysis of traffic data, it would be possible to calculate the changes in road network capacity after an earthquake by using normal traffic data, post-disaster traffic data and reduced road link capacity data, thereby enabling the identification of traffic volumes for regulation through a comparison with normal traffic levels.

In order to enhance the practicality of traffic operation systems in the aftermath of an earthquake, it is necessary to develop contingency plans for the establishment and implementation of traffic regulation. Because the extent of regulation will vary depending on the severity of the earthquake's impact on the area and traffic conditions at that time, it is required to have contingency plans for the establishment both of the areas to be regulated and the times of regulation. Depending on the scale of the earthquake, it might be necessary to coordinate a number of transportation modes such as road and railway systems, and documentation of contingency plans for these activities is also desirable. Due to the deep interrelation between all these aspects, both the physical transportation infrastructure and the system of its operation, it is essential that they be developed not as independent elements, but as an integrated system, thereby enhancing the overall efficiency of post-earthquake traffic management. Earthquakes are an unavoidable fact of life in Japan, and the need is apparent for the immediate development of a traffic management system that can maintain the functionality of the urban infrastructure even after the outbreak of a natural disaster.

The availability of timely and accurate data is a crucial element of traffic management in the aftermath of a major earthquake. The recent rapid development of ITS will ensure the provision of up-to-the-minute information about traffic conditions and alternative routes. It is only a matter of time before this technology is put to use to make available not only information about emergency traffic conditions and public transportation options but also the location of evacuation and emergency relief centers. Methodologies have been developed for the dynamic estimation of a wide range of traffic flow including generation trips, concentration trips, OD trips and route flow within the road network at every moment for each car type from direct observed link flow data. This type of estimation model will become even more accurate once the use of probe cars with individual ID numbers becomes available. It is desirable that this data be used not only by a traffic management center, but that it also be provided directly to the general public by means of every data communications media. Through the use of such high-quality data, the reliability of traffic regulation and restriction as well as dynamic route guidance throughout the road network will be enhanced.

Once this type of traffic management system utilizing ITS is put into practical use, the mandatory use of electronic ID devices by all emergency vehicles is recommended, because this will make it easy to conduct the effective management of entry permission control and dynamic route guidance in regulated areas for emergency vehicles. The use of ITS for a wide range of objectives within an effective traffic management system dealing with a variety of traffic conditions will no doubt be the focus of much further study.

Accurate prediction of the type and extent of damage caused by natural disasters is virtually impossible. Therefore it is very important to develop contingency plans for a particular scale of disaster, and provide training and experience in traffic management through the use of simulations based on hypothetical scenarios. For example, an exercise in which parameters are first specified for the region, type of disaster, location, time, scale, and extent of damage, and then road traffic conditions are simulated, and the designations of emergency routes, relief centers, evacuation areas and area regulation blocks are reviewed for effectiveness together with other components such as dynamic route guidance and traffic volume restriction. The execution of such simulations for a particular disaster scenario not only provide experience in handling traffic management under disaster conditions, but quite often reveal unexpected issues that otherwise would remain undiscovered. The repeated performance of simulations recreating a number of scenarios under a variety of cases not only enables the realization of a high level of traffic management under emergency conditions, it also ensures a capable and reliable response by traffic management system personnel in the event of an actual disaster.

7. CONCLUDING REMARKS

The establishment of a traffic management system for implementation in the event of a natural disaster involves the development of a number of contingencies related to both the physical infrastructure and the system used to manage it, all of which must be organized into an integrated system in order to produce an effective system. At present, however, this study presents merely a general overview of basic principles. There are as of yet a large number of issues to be resolved virtually in every aspect of the system, and a practical system for overall use still requires further development. It is notable however that 2-stage area traffic regulation, proposed as a new traffic management method, seems to be effective in accommodating personal passenger car demand immediately after an earthquake. The development of ITS technology has made rapid progress in recent years, and it can be expected that such technology will play a major role in the development of future traffic management systems. It is hoped that in the near future ITS technology will be integrated effectively into these systems, and that the comprehensive research will lead to the development of practical traffic management systems. In addition, the manual necessary for their implementation should be prepared as well.

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