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Application of Remote Sensing for the Prediction, Monitoring, and Assessment of Hazards and Disasters that Impact Transportation

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APPLICATION OF REMOTE SENSING FOR THE PREDICTION, MONITORING, AND ASSESSMENT OF HAZARDS AND DISASTERS THAT IMPACT TRANSPORTATION

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APPLICATION OF REMOTE SENSING FOR THE PREDICTION, MONITORING, AND ASSESSMENT OF HAZARDS AND DISASTERS THAT IMPACT TRANSPORTATION

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Although remote sensing has been used in predicting, monitoring, and assessing hazards and disasters for over 50 years, its use in the transportation domain is still in its infancy. This study was conducted to identify the research needs involving the use of remote sensing for such applications within the transportation domain. The first step taken was to determine the current state of remote sensing applications in the transportation domain associated with the prediction, monitor, and assessment of hazards and disasters. The second step was to identify the impacts that such events may cause and the information needed to prevent or reduce their impacts. With the knowledge of the required information, remote sensing requirements and technology limitations were defined. Then according to the knowledge of the current state of research and the limitations of remote systems, future research needs were identified. Finally, the Analytic Hierarchy Process (AHP) was used to rank these research needs.

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CHAPTER I

INTRODUCTION

Natural disasters happen every year and their impact and frequency seem to have greatly increased in recent decades, mostly because of environmental degradation, such as deforestation, intensified land use, and the increasing population (Vincent, 1997). We find that urban growth is extending into hazard prone regions such as low elevation areas more prone to flooding. The result is that the magnitude of the impact of a disaster increases since it is dependent on the susceptibility of the land and the vulnerability of the society (Verstappen, 1995). The vulnerability is also compounded with the increased complexity of interdependent systems (Comfort, 1999). Given that it is the transportation domain which interconnects those systems, interest has risen in determining methods which can be used to 1) measure transportation's vulnerability before such a disastrous event, 2) monitoring its availability during an event, and 3) assess the damages after an event. With today's complexity of society, response and relief from disasters has become a costly concern. Therefore, there is a need to shift to mitigation, which entails activities that strive to reduce the number of hazards and/or their impact before disasters happen (Comfort, 1999).

The purposes for using remote sensing include (Verstappen, 1995): "to investigate the susceptibility of the land and the vulnerability of the society, to construct hazard zoning maps and potential damage maps, to monitor potential hazards, and to deal with emergency situations after a disaster". Before discussing remote sensing's application in predicting monitoring, and assessing hazards and disasters, we should first define these terms. A disaster is "an event, concentrated in time and space, in which a society (or a community) undergoes severe danger and incurs such losses to its members and physical possessions (or appurtenances) that the social structure is disrupted and the fulfillment of all or some of the essential functions of the society is prevented" (Fritz 1961). A hazard is "the danger that a disaster event may develop or ensue" or "a threat to humans and what they value" (Kates, et al. 1985)

The use of remote sensing depends highly on the type of disaster or hazard of concern. Disasters or hazards can be divided into two groups, slow and rapid. In slow, "creeping" ones (e.g., desertification), remote sensing is generally used for the purpose of monitoring and low temporal resolution images are often sufficient. In rapid, "instantaneous" disasters, the required capability of remote sensing varies largely. Due to the temporal requirements of the technology, it is usually not possible to monitor rapid disasters, e.g. landslide, earthquake, etc. Sometimes there is no clear distinction between slow and rapid when labeling a disaster. For example, a flood could either be classified as slow or rapid disaster depending on the conditions under which the event occurs. No matter what type of disaster occurs, rapid or slow, there are always some clues that remote sensing system can capture and use to predict a disaster (assess the hazard), monitor its progress, and assess the impact afterwards.

The next section of this report begins with a statement of the problem this study plans to address. This will be followed by an introduction to related research in these areas, and a review of the remote sensing technologies that have been used in disaster/hazard management. Section 3 discusses how disasters impact transportation and what activities can be done to reduce or eliminate those impacts. Section 4 explores the technological requirements for using remote sensing as a means for acquiring the information needed to detect and assess common phenomena usually associated with disaster and hazards, for example, debris forced onto roadway, building damage, etc. In the last section, a proposed research agenda is presented that ranks the items on the agenda.

CHAPTER II

STATEMENT OF THE PROBLEM

Remote sensing technology has been used and studied for a long time. With the development of more and more sophisticated remote sensing sensor systems, the use of remote sensing has been given new life prompting further exploration of its use in acquiring information in agriculture, national security, oil and gas research, forestry, fisheries, disaster/hazard management, transportation, etc. Use of remote sensing technology is of interest because of its ability: 1) to provide information on a timely basis, 2) to provide large volumes of information in a cost effective manner, 3) to acquire information at hazardous or difficult to reach regions, and 4) to monitor areas and events non-intrusively.

Many research studies have been completed that employ remote sensing as the principle information source in the assessment of hazards/disasters. But, not all of the applications are suitable for use in the transportation domain, because of the higher spatial and temporal resolution required for many of the specific applications. Given the importance of transportation in our daily lives, there is a desire to ensure the safety and operation within each of the transportation domains, especially after a natural disaster. In most cases, post-disaster damages are not only due to the strength of the natural event, a large part of the damages is the result of delays in receiving, or the inadequacy of, the damage assessment information (Gamba and Casciati, 1998). This is another reason why there is a growing interest in using remote sensing to predict, monitor, and assess disasters.

Current methods utilizing remote sensing techniques applied to the assessment of hazards and disasters only cover limited portion of the transportation domain. Thus, there is a need to explore and identify the state of current research with respect to assuring transportation safety in the face of hazards and disasters and to identify future research needs in this area to promulgate the application of this growing technology within transportation.

CHAPTER III

BACKGROUND

In this report, the functions utilizing remote sensing have been labeled as prediction, monitoring, and assessment. Prediction involves acquiring necessary information that indicates the presence of a hazard. The capability to identify a hazard or predict a disaster provides opportunities for initiating prevention and mitigation activities. Therefore, given this relationship, the assessment of a hazard is equated to the prediction of the disaster. Monitoring implies tracking and recording a disaster while it is taking place. It also involves providing timely information to help those performing relief and recovery activities, as well as warning others of potential hazardous areas that may arise in the near future as a result of the disaster (e.g., movement of flood waters or fire). Assessment is a post event activity for collecting information that can be used to gauge the extent of damage to help in relief and recovery activities. Assessment also includes determining the causes of the impacts for help with future prevention activities.

To help define applications for remote sensing to predict, monitor, and assess the impact of disasters, it is first necessary that these impacts be identified. Thus the following sections will not only provide background on the current research state, but also explore the impact of different disasters on the transportation domains: roadway, railway, and pipeline.

A series of tables were developed that define the potential impacts a hazard/disaster may have on transportation. The impacts associated with each hazard/disaster are listed in a table dedicated to each domain. It is believed that any impact to transportation resulting from a hazard/disaster within these domains will cause either a partial blockage or closure of a road, rail, or pipeline, or increase the probability of the occurrence of an accident. Therefore, in the tables, the potential results of a disaster and/or hazard are grouped into these two principle categories of impacts and possible “causes” are listed for each. Each table also lists activities that can be used to eliminate or reduce identified impacts following the recognition of the cause (potentially using remote sensing technology). The development of these tables provides the information needed to determine what data is needed to support the activities listed and then to examine the potential for remote sensing technologies to be employed to supply the required information.

Remote sensing in predicting, monitoring, and assessing disasters

Remote sensing is a useful tool in predicting, monitoring, and assessing hazard/disasters. This section examines remote sensing techniques that are reported as currently being used in the area of hazard/disasters management. Paratesi (1991) divided hazard/disasters into the five groups shown in Table 1. This table lists the various hazard/disaster events belonging to each group.

Table 1. Types of Hazard/disasters (Adapted from Paratesi 1991).

Geology	**Earthquake** **Volcanism** **Landslide, mudflow** Tsunami Erosion
Hydrology	**Floods** **Flash floods** Drought **Snow** **Avalanche**
Oceanography	**Coastal flooding** Marine pollution Relative sea level rise
Meteorology	**Precipitations** **Severe local storm** **Tropical storm** **Severe winter weather** Frost and freeze **Tornado**
Vegetation	**Wildfire** Plant disease Drought Desertification Locust breeding

Given that the interest of this project is related to transportation, only those events that have a direct impact on the transportation domains will be discussed in this report. Those hazard/disaster are shown in bold in Table 1.

Among the hazard/disasters shown in the table, it is recognized that a Tsunami can have an impact on coastal transportation systems. As we know, an oceanic earthquake or a volcanic eruption may induce a tsunami. There is still no method available to exactly predict a tsunami, but a tsunami warning system has been used to assess the occurrence and predict the movement once underway (Ministry of Attorney General, 1995). Due to its unpredictable and limited impact to transportation, tsunami is not addressed in this project.

Erosion is generally a slow moving hazard that can affect the safety of transportation-related infrastructures. Erosion itself usually does not have direct and rapid impacts to transportation. However, when combined with some disasters, erosion may worsen and accelerate the onset of the damages. For example, the occurrence of a flash flood may increase the rate of erosion and thus increase the possibility of damage to infrastructures. Also, erosion may increase the probability of a landslide. Thus, in managing a disaster, in which erosion has a critical impact, erosion should be considered a factor that may contribute to a disaster's impact and included as a component in the management system. Therefore, this study will not directly discuss erosion since it will be inherently considered a factor within each disaster where erosion occurs.

Since the duration of flash floods is so short, it is hard to predict and monitor a flash flood. Aside from the temporal resolution, the remote sensing requirements for assessing a flash flood are similar to those for assessing a normal flood. Therefore, this report does not address flash floods specifically, but aside from temporal limits the technological requirements and research needs discussed in the sections relating to normal floods can be applied.

Drought, marine pollution, sea level rise, plant disease, desertification, and locust breeding have no direct relation to transportation and thus will not be included in the project. Frost and freeze conditions have an impact on transportation. However, frost and freeze conditions are currently being handled by other ground based sensor systems and not particularly of interest due to these existing programs (Perry, 1997).

Storms

Among these disasters, storms (severe local storm, tropical storm) can cause a lot of damage and money lost every year. Except for its direct impact to transportation, a storm may also induce some other disaster, such as floods and tornados. Given that the use of remote sensing, both ground based and air based, to detect and monitor a storm is well established and has been used for a long time, we will not discuss it in the following section. However, the direct impacts of storms are listed in Table 2, Table 3, and Table 4.

Table 2. Storm's impacts to roadway.

Impact	Cause	Activity
Block or close roadway	Debris forced onto roadway (branches, etc. from wind and water)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch team to clear up roadway
	Stranded vehicles on roadway (malfunction, stuck, etc.)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch tow truck
Increase the probability of accidents occurring	Degradation in road surface conditions (slippery, soft shoulders or road (if dirt), etc)	Set up temporary warning signal
	Debris forced onto roadway (branches, etc. from wind and water)	Dispatch team to clear up roadway
		Set up temporary warning signal
	Loss of traffic signals or signs (loss of electric power)	Dispatch repair team
		Send out police officers
		Set up temporary warning signal
	Concealed traffic signs	
	Greater variation in traffic (speed, stopping on shoulders, etc)	Set up temporary warning signal
	Degradation in visibility (rain, fog, etc.)	
	Congestion on roadway (stranded vehicles, accidents, objects, etc.)	Create alternative route(s)
		Dispatch team to clear up roadway
		Send out police officers
		Dispatch tow truck

* Storm may induce flood, landslide, or tornado.

Table 3. Storm's impacts to railway.

Impact	Cause	Activity
Block or close railway due to:	Debris forced onto railway (branches, etc. from wind and water)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Inform train conductor of hazard location
		Dispatch team to clear up roadway (railway)
		Scheduling
	Stranded vehicles or train on railway (malfunction, stuck, derailment, etc.)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
		Evacuate passenger
		Dispatch ambulance and first-aid staff
		Dispatch tow truck
Increase the probability of accidents occurring due to:	Degradation on railway conditions (slippery, loss of ballast, etc.)	Dispatch repair team
		Inform train conductor of hazard location
	Debris forced onto railway (branches, etc. from wind and water)	Inform train conductor of hazard location
		Dispatch team to clear up roadway (railway)
	Loss of traffic signals (loss of electric power)	Dispatch repair team
		Inform train conductor of hazard location
		Send out police officers
		Set up temporary warning signal
	Concealed traffic signs (rain, fog, etc.)	Inform train conductor of hazard location
	Degradation in visibility (rain, fog, etc.)	Inform train conductor of hazard location

* Storm may induce flood, landslide, or tornado.

Table 4. Storm's impacts to pipelines.

<table>
<tr><td>Impact</td><td>Cause</td><td>Activities</td></tr>
<tr><td rowspan="4">Close the pipeline</td><td rowspan="3">Damages to pipeline (from objects forced onto pipeline)</td><td>Cut off pipeline supply</td></tr>
<tr><td>Dispatch repair team</td></tr>
<tr><td>Dispatch team to clear up objects onto pipeline</td></tr>
<tr><td>Presence of potential hazard</td><td>Cut off pipeline supply</td></tr>
<tr><td rowspan="4">Increase the probability of pipeline damage</td><td rowspan="2">Pipeline breakage or distortion (from weight of objects forced onto pipeline)</td><td>Dispatch team to clear up objects onto pipeline</td></tr>
<tr><td>Dispatch repair team</td></tr>
<tr><td rowspan="2">Damages to pipeline facilities or infrastructure (from objects forced onto pipeline, etc.)</td><td>Dispatch team to clear up objects onto pipeline</td></tr>
<tr><td>Dispatch repair team</td></tr>
</table>

* Storm may induce flood, landslide, or tornado.

Wildfire

Wildfires not only result in economic loss but also have a large impact on the environment, e.g., unbalance of carbon cycle, pollution of atmosphere, deforestation, and a climate impact (Leibrandt and Rico, 1998). However, not all forest fires should be suppressed immediately. Some prescribed fires and natural ignited fires are used as treatment for plant disease and are good for our natural ecosystem (Prevedel, 1995).

The United Stated Forest Service (USFS) has used fire potential indices to forecast the likelihood of wildfires. These indices are based on ground and remote sensing observations. Minardi et al. (1999) use a statistical-base fuel model to predict the occurrences of wildfire. The input of this model includes fuel type, elevation, precipitation, relative humidity, temperature, and historic record. Among these inputs, fuel type (forest type), precipitation, relative humidity, and temperature can be acquired with low spatial resolution (1 km or more), higher spatial resolution is necessary for monitoring changes in this data.

Since forests are usually spread broadly, remote sensing therefore becomes a most promising tool for use in wildfire management. Remote sensing is capable of being used in risk prevention to monitor vegetation status for early detection, to monitor fire progress, and to assess the damage inflicted. The most useful band in fire detection is mid-infrared data (3um~5um); visible, thermal infrared, and near-infrared bands are also useful (Leibrandt and Rico, 1998). However, optical images are not always available because of the appearance of cloud and haze cover during wildfire events (Siegert et al., 1999). Kudoh (1999) and Siegert et al. (1999) also found that the use of AVHRR channel 3A (1.6 μm) on NOAA-15 is effective in fire detection. Because the observation of wildfires is largely dependent on the infrared channel, an additional heat source, especially the sun, may highly aggravate the observation (because a pixel in the image is easily saturated by an additional heat source, a single pixel of 1.1 km^2 area can be saturated by a fire on an offshore oil platform). There are several factors that affect the detection and monitoring the wildfire (Prevedel, 1995; Siegert et al., 1999):

Nadir – The perpendicular position of the remote sensing sensor to a ground target. Nadir is fixed for each satellite system. It will affect the view angle and view distance for each system.

Time of observation - Solar heating affects the temperature of ground objects. The observation time thus becomes critical to avoid misinterpretation.

Cloud cover– The appearance of clouds will block or degrade the observation of the remote sensing sensor.

Sun reflection – This is also the problem of observation time. It happens when, for example, a satellite is west of target and sun is east of target.

The speed at which forest fires spread is largely dependent on vegetation state, topography, and meteorological factors, such as weather and moisture. Therefore, in wildfire monitoring and detection, not all of a region will need to have the same review frequency. Generally speaking, in fire detection, recommendations state that the temporal resolution should not more than 15 minutes and the spatial resolution is approximately 500 m (Leibrandt and Rico, 1998). Likewise, in monitoring of fire, a temporal resolution of 90 minutes is favored with a spatial resolution about 35m (Leibrandt and Rico, 1998).

Using an optical base image in assessment of a burned area after the event is difficult because of rapid re-growth of vegetation. In the contrast, in radar images, there is a great change in image texture because the backscatter is different in a burned area compared to a healthy vegetation area. Burned areas are darker in radar images because of the low backscatter characteristic of dry soil (Siegert et al., 1999). Siegert et al. (1999) suggest using high temporal resolution but low spatial resolution system, such as NOAA-AVHRR, in tracking the spreading of wildfire. Combining the radar images and ground information, such as landuse/landcover, in a geographic information system (GIS) environment enhances assessment of the impact of wildfires.

Table 5. Wildfire's impacts to roadway.

Impact	Cause	Activity
Block or close roadway	Presence of potential hazard	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Set up temporary warning signal
	Heavy smoke (very low visibility) or fire	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Send out fire team
		Evacuate area
	Damage to roadway (from heat)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
	Debris forced onto roadway (fallen trees or structures)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch team to clear up roadway (railway)
Increase the probability of accidents occurring	Damage or loss of traffic signals (loss of electric power)	Dispatch repair team
		Send out police officers
		Set up temporary warning signal
	Damage to traffic signs following event	Dispatch repair team
		Set up temporary warning signal
	Degradation in visibility (smoke)	Set up temporary warning signal
	Congestion on roadway (evacuation, accidents, etc)	Create alternative route(s)
		Send out police officers
		Dispatch tow truck

Table 6. Wildfire's impacts to railway.

Impact	Cause	Activity
Block or close railway	Presence of potential hazard	Close all or part of railway
		Create alternative route(s)
		Inform train conductor of hazard location
		Scheduling
	Heavy smoke or fire	Close all or part of railway
		Inform train conductor of hazard location
		Scheduling
		Send out fire team
	Damage to railway (from heat)	Close all or part of railway
		Create alternative route(s)
		Create alternative route(s)
		Inform train conductor of hazard location
		Scheduling
	Debris forced onto railway (fallen trees or structures)	Close all or part of railway
		Inform train conductor of hazard location
		Dispatch team to clear up railway
		Scheduling
Increase the probability of accidents occurring	Damage or loss of traffic signals (loss of electric power)	Create alternative route(s)
		Inform train conductor of hazard location
		Set up temporary warning signal
	Degradation in visibility (smoke)	Inform train conductor of hazard location

Table 7. Wildfire's impacts to pipelines.

Impact	Cause	Activities
Close the pipeline	Explosion of pipeline (from heat, objects forced onto pipeline)	Cut off pipeline supply
		Sent out fire team
		Dispatch repair team
	Damages to pipeline (from heat, objects forced onto pipeline)	Cut off pipeline supply
		Dispatch repair team
		Send out fire team
		Dispatch team to clear up objects onto pipeline
	Presence of potential hazard	Cut off pipeline supply
Increase the probability of pipeline damage	Pipeline breakage or distortion (from heat, weight of objects forced onto pipeline)	Send out fire team
		Dispatch team to clear up objects onto pipeline
		Dispatch repair team
	Damages to pipeline facilities or infrastructure (from objects forced onto pipeline, heat, etc.)	Dispatch team to clear up objects onto pipeline
		Send out fire team
		Dispatch repair team

Earthquake

An earthquake is caused by a sudden displacement of the earth's crust. This sudden movement produces seismic waves that result in vibration when they arrive at the earth's surface. The primary damages caused by earthquakes are destruction of structures, breakdown of transport activities, loss of public utilities, etc. To complicate matters, at times earthquakes may trigger other hazards, e.g. landslides, fires, floods, and tsunamis. The strength of an earthquake is measured by magnitude and intensity. Magnitude is the physical energy released, where intensity is an earthquake's effect on the earth's surface. Some aspects of an earthquake are predictable, as we will discuss latter. However, today's technology is still not able to precisely predict its time and location. And the whole event usually last for only a few seconds, making it near impossible to monitor an earthquake with a synoptic view.

Earthquakes are the result of plate movement. This movement will produce stress in the earth's crust, and thus cause small changes in surface topography. Digital elevation models (DEMs), or digital terrain models are critical in the study of crustal motions, and can be used to predict, and to assess an earthquake's impact after the event (Massonnet, 1995). Two types of remote sensing images can be used as input to build DEMs, e.g. high-resolution digital photogrammetry and interferometric synthetic aperture radar (InSAR) (Vincent, 1997). The spatial resolution requirement of the former must be less than or equal to 1 meter. Photogrammetry also needs at least two sets of different temporal digitized stereo images to identify the differences in topology, and it needs a few years of data collecting in order to build the topography database. The InSAR method is more dynamic and has a higher spatial resolution on the order of a few centimeters. It also needs two images collected from different orbit positions (Vincent, 1997). However, an InSAR system requires a stable flight path and flying speed. Thus, a satellite-based system would be preferred to an airborne system. But airborne InSAR systems are also useful when some additional information, such as GPS data, is added to compensate for the drifts of the airborne system.

An anomalistic increase in the temperature of the earth's surface is another precursor used to predict an earthquake. The temperature rise is not only relative to the charged particles while rocks are under stress but is also relative to the release of methane and carbon dioxide (Vincent, 1997). Qiang Zuji and Dian Changgong (1993) use thermal infrared bands of METEOSAT to collect the temperature changes in earthquake prone regions with a temporal resolution twice per hour. They have successfully predicted some earthquakes (Vincent, 1997). Since methane (CH_4) is also a precursor of earthquakes, one could also employ an infrared sensor to detect changes in methane concentrations (Vincent, 1997). However, although these two methods are able to predict an earthquake, they are still not accurate enough to provide useful information for disaster management.

With respect to assessing the post-event impacts of an earthquake, a ground-based survey is usually not a viable option because of access problems due to the resultant road damage and traffic jams. Remote sensing systems thus play a critical role in providing timely information to help assess the impact and plan relief activities. Damage to structures is always an index to an earthquake's impact, and a spatial resolution of 2 meters is necessary to detect the changes in the structures (Gamba and Casciati, 1998). High spatial resolution images from all kinds of remote sensing systems, such as radar images and photographs (both airborne and space-born), have been proven useful in assessing damages to buildings and other infrastructures (Gamba and Casciati, 1998). Also, about the acquisition of timely images, there are a lot of different recommendations that range from 6 to 48 hours after the event (Ozdogan and El-Baz, 2000). Airborne systems are able to meet this spatial resolution requirement, but, because of the large-scale impact of an earthquake, it is difficult and time-consuming to use airborne systems to provide the necessary coverage. Many spaceborne systems, however, generally don't have the required spatial resolution, but future satellite sensors should be able to support this technological need.

Outside of the spatial resolution requirements, a second problem is that it’s not guaranteed that a satellite will be in the right spot to provide the timely images needed. Therefore, Ozdogan and El-Baz (2000) suggest using moderate resolution satellite images for timely initial damage assessment. In their study, they used two Landsat TM images of western Turkey, one is pre-event image and the other one was acquired seven hours after the event. Multi-temporal images are required to compare the differences over the same area. The result shows that moderate resolution satellite images are capable of providing synoptic and large scale assessment, because of the albedo values (the fraction of incident radiation that is reflected by a surface) are generally increased in visible and infrared bands because of exposed material and reduced shadow (Ozdogan and El-Baz, 2000).

Table 8. Earthquake's impacts to roadway.

Impact	Cause	Activity
Block or close roadway	Damage to roadway (disjointed surfaces, openings, etc.)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
	Debris forced onto roadway (from fallen or collapsed structures, trees, etc.)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
		Dispatch team to clear up roadway (railway)
		Set up temporary warning signal
	Stranded vehicles on roadway (driver flees, stuck, etc.)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch tow truck
Increase the probability of accidents occurring	Loss of control of vehicle	
	Debris forced onto roadway (from fallen or collapsed structures, trees, etc.)	Dispatch team to clear up roadway (railway)
		Set up temporary warning signal
	Loss of traffic signals (loss of electric power)	Dispatch repair team
		Send out police officers
		Set up temporary warning signal
	Concealed or displaced traffic signs	Dispatch repair team
	Greater variation in traffic (speed, stopping on shoulders, etc)	Set up temporary warning signal
	Congestion on roadway (evacuation, stranded vehicles, accidents, objects, etc)	Create alternative route(s)
		Dispatch team to clear up roadway (railway)
		Send out police officers
		Dispatch tow truck

* Earthquake may induce landslide, tsunami, flood (from damage to a dam), fire, or volcano.

Table 9. Earthquake's impacts to railway.

Impact	Cause	Activity
Block or close railway	Damage to railway (distortion, openings, etc.)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
		Inform train conductor of hazard location
	Stranded vehicles or train on railway (malfunction, derailment, etc.)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
		Evacuate passenger
		Dispatch ambulance and first-aid staff
		Dispatch tow truck
	Debris forced onto railway (from fallen or collapsed structures, trees, etc.)	Close all or part of roadway/railway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
		Inform train conductor of hazard location
		Dispatch team to clear up roadway (railway)
		Scheduling
Increase the probability of accidents occurring	Debris forced onto railway (from fallen or collapsed structures, trees, etc.)	Dispatch repair team
		Inform train conductor of hazard location
		Dispatch team to clear up roadway (railway)
		Scheduling
	Loss of traffic signals of signs (loss of electric power)	Dispatch repair team
		Inform train conductor of hazard location
		Send out police officers
		Set up temporary warning signal
	Concealed or displaced traffic signs	Dispatch repair team
		Inform train conductor of hazard location

* Earthquake may induce landslide, tsunami, flood (from damage to a dam), fire, or volcano.

Table 10. Earthquake's impacts to pipelines.

Impact	Cause	Activities
Close the pipeline	Explosion of pipeline (from heat, objects forced onto pipeline)	Cut off pipeline supply
		Sent out fire team
		Dispatch repair team
	Damages to pipeline (from heat, vibration, objects forced onto pipeline)	Cut off pipeline supply
		Dispatch repair team
		Send out fire team
		Dispatch team to clear up objects onto pipeline
Increase the probability of pipeline damage	Above ground lines being buried underground	Dispatch repair team
		Dispatch team to uncover the pipeline
	Pipeline breakage or distortion (from heat, weight of objects forced onto pipeline, or vibration)	Send out fire team
		Dispatch team to clear up objects onto pipeline
		Dispatch repair team
	Damages to pipeline facilities or infrastructure (from objects forced onto pipeline, vibration, heat, etc.)	Dispatch team to clear up objects onto pipeline
		Send out fire team
		Dispatch repair team

* Earthquake may induce landslide, tsunami, flood (from damage to a dam), fire, or volcano.

Landslide (Avalanche)

Landslide is a rapid disaster that usually happens in an unstable slope region, which always includes the falling, sliding, or flowing of soil and rock. Every year, landslides also cause the death or injury of thousands of people and millions of dollars of property lost (Raju and Saibaba, 1999). Landslide can be categorized according to the form and amount of mass 1) block slides, 2) fan/cone slides, and 3) debris/ mudflows (Raju and Saibaba, 1999). There are many factors that affect or trigger the potential of a landslide, they are (Singhroy et al., 1998, 1995; Raju and Saibab, 1999):

Slope – most landslides occur when slopes are between 15^o and 45^o

Landuse – landslides are likely to happen in barren lands, human activities like deforest, and fallow lands will increase the probability of a landslide.

Tectonic elements –tectonic movement such as in an earthquake can trigger a landslide.

Climate – heavy rainfall/snowfall will largely increase the probability of a landslide.

Human activities – such as road construction, mining, agriculture, etc. will increase the probability of a landslide.

Geological type – Shikada et al. (1997) point out that landslide potential is relative to vegetation and geological type. In their study areas, most of the landslide prone areas are made of Andesite and Mudstone, where most of the vegetation cover is cedar. In order words, vegetation cover is an index for geological type, which is an index for landslide.

Landslides are predictable if terrain characteristics are available. However, it's impossible to exactly predict when and where a landslide will occur because the relationship between the factors mentioned above is complex (Shikada et al. 1997). And since the whole landslide process usually last for only a few seconds, it's usually not possible to monitor it.

In order to predict and map landslide prone areas, the capability to identify ground features is necessary because it may provide clues to potential hazardous zones. Traditional point-by-point measurement of geographic data is precise but very time consuming and costly, it's hard to map and analyze enormous volumes of terrain characteristics (Thompson and Howarth, 1996). Some geographic features that can be used to produce a landslide hazard map include landcover/ landuse type, slope, tectonics, geology, etc. (Thompson and Howarth, 1996; Raju and Saibaba, 1999). With this information, protective measures can be employed along transportation routes and pipelines (Singhroy et al., 1998) within identified landslide hazard zones.

Monitoring ground features and ground movement requires higher spatial resolution satellite data. Systems such as TM (thematic mapper) and SPOT, generally don't offer enough resolution unless merged with other high-resolution images (Singhroy et al., 1998). Radar imaging thus becomes a more promising resource. The spatial resolution of airborne SAR (synthetic aperture radar) can be less than 1 m. In order to provide other land cover information, such as vegetation and soils, a TM image is used in combination with the SAR image. The resulting SAR/TM images will have different colors to represent different landslide features, e.g. rock slump, block slide, scars, faults, rupture line, and debris lobe (Singhroy, 1995).

InSAR (Interferometric synthetic aperture radar) is another technology for monitoring ground features and ground movements. Its satellite-based spatial resolution can be as small as a few centimeters (Grivas et al., 1998). One of the most useful applications is InSAR derived DEMs (digital elevation model), which can measure changes as small as a few centimeters over time. Another advantage of using InSAR to derive DEMs is that it doesn't need to include any correlation process (Singhroy et al., 1998). But, the acquisition of airborne InSAR is difficult in that it requires precisely repeating flightpaths (Grivas et al., 1998). The information provided by a GPS may be added to compensate vertical and horizontal drift (Singhroy et al., 1998).

SAR/TM and InSAR images are useful for monitoring ground features and ground movements. InSAR has a better representation of elevation and slope changes, while SAR/TM is good for characterizing retrogressive slope failures and flow features (Singhroy et al., 1998). These techniques can be integrated with traditional airborne photographs that are currently used for landslide survey. Some criteria for using remote sensing images in recognizing landslide are as follow (Raju and Saibaba, 1999):

- Abrupt tonal and textural variations
- Detached blocks of hills separated by arcuate/rectangular escarpments
- Exposure of fresh rock surfaces along the landslide planes
- Spread of large volumes of detached material near the foothills
- Extensive point bar deposits, river terraces and shift in the river course at places

In the aspect of assessment of the impact of landslides, different data layers (such as landuse/ landcover, DEM, infrastructures, etc.) can be overlaid and analyzed in a GIS system.

Table 11. Landslide's impacts to roadway.

Impact	Cause	Activity
Block or close roadway	Presence of potential hazard	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
	Damage to roadway	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
	Debris forced onto roadway (Mud, rock, etc.)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch team to clear up roadway
	Stranded vehicles on roadway (crushed or damaged from falling debris)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch team to clear up roadway
		Dispatch tow truck
Increase the probability of accidents occurring	Degradation in road surface conditions (slippery if mud, etc)	Set up temporary warning signal
	Debris forced onto roadway (Mud, rock, etc.)	Dispatch team to clear up roadway
		Set up temporary warning signal
	Destroyed or concealed traffic signs or signals	Dispatch repair team
		Set up temporary warning signal
	Congestion on roadway (stranded vehicles, accidents, objects, etc)	Create alternative route(s)
		Dispatch team to clear up roadway
		Send out police officers
		Dispatch tow truck

Table 12. Landslide's impacts to railway.

Impact	Cause	Activity
Block or close railway	Presence of potential hazard	Close railway
		Create alternative route(s)
		Inform train conductor of hazard location
	Damage to railway	Close railway
		Create alternative route(s)
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
	Debris forced onto railway (Mud, rock, etc.)	Close railway
		Inform train conductor of hazard location
		Dispatch team to clear up railway
		Scheduling
	Stranded vehicles or train on railway (crushed or damaged from falling debris, derailment, etc.)	Close railway
		Dispatch repair team
		Inform train conductor of hazard location
		Dispatch team to clear up railway
		Scheduling
		Evacuate passenger
		Dispatch ambulance and first-aid staff
		Dispatch tow truck
Increase the probability of accidents occurring	Degradation in railway condition (mud on railway, lost of ballast, etc.)	Dispatch repair team
		Inform train conductor of hazard location
	Debris forced onto railway (Mud, rock, etc.)	Inform train conductor of hazard location
		Dispatch team to clear up railway
	Destroyed or concealed traffic signs or signals	Dispatch repair team
		Inform train conductor of hazard location
		Send out police officers
		Set up temporary warning signal

Table 13. Landslide’s impacts to pipelines.

Impact	Cause	Activities
Close the pipeline	Explosion of pipeline (from objects forced onto pipeline)	Cut off pipeline supply
		Sent out fire team
		Dispatch repair team
	Damages to pipeline (from vibration, objects forced onto pipeline)	Cut off pipeline supply
		Dispatch repair team
		Dispatch team to clear up objects onto pipeline
	Presence of potential hazard	Cut off pipeline supply
Increase the probability of pipeline damage	Above ground lines being buried underground	Dispatch repair team
		Dispatch team to uncover the pipeline
	Pipeline breakage or distortion (from, weight of objects forced onto pipeline, or vibration)	Dispatch team to clear up objects onto pipeline
		Dispatch repair team
	Damages to pipeline facilities or infrastructure (from objects forced onto pipeline, vibration, etc.)	Dispatch team to clear up objects onto pipeline
		Dispatch repair team

Flood

Floods are one of the most widespread natural disasters and cause damage to both agricultural crops and properties. The presence and magnitude of flood-hazards are relative to the associated human activities, such as the concentration of population living in low altitude areas, these activities may lead to retarding the hazard-reduction efforts or increasing the extent of damages due to flooding (Chen, 1999). Because a flood can be either a slow or rapid disaster, the effort needed for monitoring a flood is similar to assessing the damages caused by flood. Thus, monitoring floods is not only necessary for planning relief activities, but is also necessary to shift from relief to long-term flood mitigation planning. There are several types of flood hazards: stream flooding, tidal floods, and waterlogging. Aerial observation is often impossible due to the bad weather and may be very time consuming because of the large inundation areas during the event. Satellite remote sensing systems that can penetrate cloud cover could thus provide a quick and cost effective source for flood related information.

Timely information about a flood's extent, intensity, duration, and impact can help to reduce its damages (Kogan, 1998). Chen (1999) used a flood/waterlogging hazard management system (M-ISM) for coastal plain lowlands. This system uses the information from two sub-systems, hazard-causing environment system (E-ISM) and hazard-delimiting system (D-ISM). Factors they used to build the different systems are given in Table 14.

As we can see, some information used by the hazard management system can be derived directly or indirectly from remote sensing techniques. This information includes land use pattern, ground surface elevation, ground surface gradient, soil type, vegetation and crop type, surface water level, tidal level, and atmospheric conditions.

Geological information is an important factor in flood prediction and risk assessment, because geo-structure is the main cause of run-off trends, erosion trends, and water stagnation (Baggio and Massironi, 1998). "The reconstruction of a geo-mechanical-fracturing model of the rock substratum can be the main element to localize the lower plane areas that probably draw the flood (Baggio and Massironi, 1998)." Satellite multispectral data is useful in recognition of important tectonic elements. From these tectonic elements, a tectonic model can be created.

Table 14. Factors used in M-ISM, E-ISM, and D-ISM.

M-ISM	E-ISM	D-ISM
Land use pattern	Ground surface elevation	Ground subsidence
Protection capacity of the levees	Ground surface gradient	Sea-level rising
Pumping/drainage capacity	Soil type	Storm surge influx
Retention Storage capacity	Vegetation and crop type	Heavy and long-duration precipitation processes
Legislation and insurance policies	Precipitation amount	Water levels
Investment	Runoff	Hazard-impacted area
Hazard monitoring and forecasting	Groundwater depth	Future climate warming
Contingency plans and hazard-reduction planning	Surface water level	Water surface gradient
Economic production structure	Tidal level	
Hazard awareness	Atmospheric conditions	
	Background of Quaternary geology	
	Storm surge	
	Astronomic factors	

The capability to distinguish between flooded area, normal water bodies, and land is essential in flood assessment (Islam and Sado, 1998). In order to gain early assessment and a synoptic view of flooding, Chen et al. (1999) used the Defense Satellite Meteorological Program (DMSP) Special Sensor Microwave/Imager (SSM/I) to monitor the flood in China. The reason for choosing SSM/I is 1) it's a passive microwave sensor and thus can penetrate thick cloud cover and 2) it has a high temporal resolution (6 hours revisit time). However, the low spatial resolution of SSM/I (12.5 km and 25 km) restricts its ability to provide more detailed information.

For most optical sensors, the near-infrared (NIR) band is generally used to detect water bodies because of its lower reflectance compare to other land objects (Takeuchi, et al. 1999). Using multi-temporal images, both pre- and post-event images have been recommended to tell the differences between ground features since sometimes it's difficult to identify ground changes using a single image. Then the DEMs can be combined with the images to produce flooded area elevation models (Islam and Sado, 1998). Although most of the current spaceborne optical sensors support improved temporal resolutions and larger swath widths, due to the fact that bad weather may reduce the visibility of optical sensors, passive optical images can often be useful several days after the event for monitoring the flooded areas. Techniques exist that can distinguish between water bodies and land in thin cloud and cloud shadow areas (Sheng et al., 1998). However, there is still no optic-based method to deal with situations when clouds are thick.

In contrast, spaceborne active radar, because of its penetration capacity and all weather characteristics, is excellent in capturing real time or near real time images in all weather and day or night condition (Maggi et al., 1998; Mahmood and Parashar, 1999; Takeuchi et al. 1999). Mahmood and Parashar (1999) use Canada's RADARAST-1 satellite to monitor the flood condition in Bangladesh. The flooded land areas are detectable in a radar image because the tone changes from dark to dark gray as the amount of water and inundated objects increase. Because the advanced Synthetic Aperture Radar (SAR) system on the RADARAST-1 satellite, it is possible to select image parameters (angle of the incident beam, the width of the imaging swath, and the ground resolution) and the instantaneous view of flood areas in Bangladesh is acquired in a single image at a certain time. Takeuchi et al. (1999) claimed that using single SAR images in distinguishing water body and landcover is possible because of water's low backscattering characteristic in a RADAR image. However, it is sometimes difficult to distinguish between a water body and various landcover types only by backscatter. Thus, in their study, they use multi-temporal images, pre- and post-event, acquired from JERS-1 SAR and compare the backscatter of the two images. Radar images still have some inherent shortages, such as distortion and complex comprehension of acquired signals, which make preprocessing of radar images necessary.

In the view of transportation, since it is possible to distinguish between water bodies and land from remote sensing images (passive and active), the combination of a GIS system and remote sensing images is useful in determining what roads are accessible, and therefore, aid in managing efforts to close roads and devise new routes.

For long-term flood or water logging hazards, vegetation stress is another index for assessing soil moisture. VCI (Vegetation Condition Index) and TCI (Temperature Condition Index) are two indexes to identify vegetation condition. VCI is derived from visible and near infrared bands, and TCI is derived from thermal band. If vegetation stress is the result of excessive soil moisture, then VCI will decrease in value. In flood areas, the surface temperature will decrease, resulting in a decrease in TCI (Kogan, 1998). Thus, the combination of TCI and VCI measures not only can be use to assess water logging type flood, but also it can be used to identify wildfire prone areas.

Table 15. Flood's impacts to roadway.

Impact	Cause	Activity
Block or close roadway	Presence of potential hazard	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Evacuate area
	High water	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
	Damage roadway	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
	Debris forced onto roadway	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch team to clear up roadway
	Stranded vehicles on roadway (malfunction, stuck, etc)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch tow truck
Increase the probability of accidents occurring	Debris forced onto roadway	Dispatch team to clear up roadway
	Degradation in road surface conditions	Set up temporary warning signal
	Loss of traffic signals (loss of electric power)	Create alternative route(s)
		Send out police officers
	Concealed traffic signs	
	Greater variation in traffic (speed, stopping on shoulders, etc)	Set up temporary warning signal
	Congestion on roadway (evacuation, stranded vehicles, accidents, objects, etc)	Close all or part of roadway (use barricade & signals as appropriate)
		Send out police officers
		Dispatch tow truck

Table 16. Flood's impacts to railway.

Impact	Cause	Activity
Block or close railway	Presence of potential hazard	Close railway
		Create alternative route(s)
		Inform train conductor of hazard location
		Scheduling
	High water	Close railway
		Create alternative route(s)
		Inform train conductor of hazard location
		Scheduling
	Damage railway	Close railway
		Create alternative route(s)
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
	Debris forced onto railway	Close railway
		Inform train conductor of hazard location
		Dispatch team to clear up railway
		Scheduling
	Stranded train on railway (malfunction, derailment, etc.)	Close railway
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
		Evacuate passenger
		Dispatch ambulance and first-aid staff
		Dispatch tow truck
Increase the probability of accidents or occurring	Debris forced onto railway (from water flow)	Inform train conductor of hazard location
		Dispatch team to clear up railway
		Scheduling
	Degradation in railroad conditions	Dispatch repair team
		Inform train conductor of hazard location
	Loss of traffic signals or signs (loss of electric power)	Dispatch repair team
		Inform train conductor of hazard location
		Send out police officers
		Set up temporary warning signal

Table 17. Flood's impacts to pipelines.

Impact	Cause	Activities
Close the pipeline	Damages to pipeline (from objects forced onto pipeline	Cut off pipeline supply
		Dispatch repair team
		Dispatch team to clear up objects onto pipeline
	Presence of potential hazard	Cut off pipeline supply
Increase the probability of pipeline damage	Pipeline breakage or distortion (from weight of objects forced onto pipeline)	Dispatch team to clear up objects onto pipeline
		Dispatch repair team
	Damages to pipeline facilities or infrastructure (from objects forced onto pipeline, etc.)	Dispatch team to clear up objects onto pipeline
		Dispatch repair team

Volcano

Volcanoes are the result of endogenous energy that must be released from the earth. Volcanoes are classified as rapid disasters, however, since their potential locations are known and the whole processes may last up to several days. It gives remote sensing systems sufficient time to monitor the activities of volcanoes at intervals from beginning to the end. Volcanic hazards can be divided into five types; they are pyroclastic currents, lahars or mudflows, lava flows, tephra fall, and lava doming (Slob et al., 1998).

With respect to predicting the eruption of a volcano and assessing volcanic risk, satellite remote sensing can help to provide volcanic information concerning soil deformation, temperature, gases, and aerosols (Gregori, 1995). Abnormal temperature is a precursor to an active volcano. Zuji and Changgong (1993) have successfully used thermal bands on METEOSAT (spatial resolution of 2.3 km) to detect the abnormal increases in temperature, and have successfully predicted two volcanic eruptions several days earlier than they took place. Another precursor is the formation of lava domes, shortwave infrared sensors and thermal infrared bands are useful in monitoring the formation of lava domes. A lava dome is formed on the active volcanic vent if lava is too viscous to flow. Since lava domes are often found on volcanoes that erupt explosively, the growth of lava domes is useful information to assist in predicting volcano eruption, and pyroclastic flow hazards (Wooster et al., 1998). Monitoring lava domes doesn't require high spatial resolution. Generally speaking, shortwave infrared and thermal infrared bands with a spatial resolution of 1 km is suitable for monitoring the formation of lava domes.

Small ground movements are a precursor to assess the activity of a volcano. Radar images are suitable for small ground movement monitoring. However, radar images have inherent disadvantage, e.g. large distortions in the mountainous areas due to topographic differences. Processes such as ortho-rectification and geo-referencing have to be performed in order to obtain accurate morphological features (Slob, 1998).

Visible and near-infrared bands are useful in volcanic activities monitoring. In (Tanaka et al., 1998), they used three satellite sensors, e.g. SPOT/HRV, Landsat/TM, and MOS/MESSR, to monitor and assess volcanic activities. The result shows that visible and infrared bands are useful in observing pyroclastic and debris flows.

Table 18. Volcano's impacts to roadway.

Impact	Cause	Activity
Block or close roadway due to:	Presence of potential hazard	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Evacuate area
	Destroyed roadway	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
		Built temporal road
	Damage to roadway	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
	Debris forced onto roadway (lava, ash)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch team to clear up roadway
Increase the probability of accidents occurring due to:	Degradation in road surface conditions (from ash)	Set up temporary warning signal
	Debris forced onto roadway (ash, rock, etc.)	Dispatch team to clear up roadway
	Loss of traffic signals or signs (loss of electric power)	Dispatch repair team
		Send out police officers
		Set up temporary warning signal
	Concealed traffic signs	
	Degradation in visibility (ash and smoke)	
	Congestion on roadway (evacuation, accidents, objects, etc)	Create alternative route(s)
		Dispatch team to clear up roadway
		Send out police officers
		Dispatch tow truck

Table 19. Volcano's impacts to railway.

Impact	Cause	Activity
Block or close railway due to:	Presence of potential hazard	Close all or part of railway
		Create alternative route(s)
		Inform train conductor of hazard location
	Damage to railway	Close all or part of railway
		Create alternative route(s)
		Dispatch repair team
		Inform train conductor of hazard location
		Build temporary railroad
		Scheduling
	Debris forced onto railway (rock, ash)	Close all or part of railway
		Inform train conductor of hazard location
		Dispatch team to clear up railway
		Scheduling
	Stranded vehicles or train on railway (crushed or damaged from falling debris, derailment, etc.)	Close all or part of railway
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
		Evacuate passenger
		Dispatch ambulance and first-aid staff
		Dispatch tow truck
Increase the probability of accidents occurring due to:	Degradation on railroad condition (from ash)	Inform train conductor of hazard location
		Dispatch team to clear up railway
	Debris forced onto railroad (ash, rock, etc.)	Inform train conductor of hazard location
		Dispatch team to clear up railway
	Loss of traffic signs and signals	Dispatch repair team
		Inform train conductor of hazard location
		Set up temporary warning signal
	Degradation in visibility (smoke and ash)	Inform train conductor of hazard location

Table 20. Volcano's impacts to pipelines.

Impact	Cause	Activities
Close the pipeline	Explosion of pipeline (from heat, objects forced onto pipeline)	Cut off pipeline supply
		Sent out fire team
		Dispatch repair team
	Damages to pipeline (from heat, vibration, objects forced onto pipeline)	Cut off pipeline supply
		Dispatch repair team
		Send out fire team
		Dispatch team to clear up objects onto pipeline
	Presence of potential hazard	Cut off pipeline supply
Increase the probability of pipeline damage	Above ground lines being buried underground	Dispatch repair team
		Dispatch team to uncover the pipeline
	Pipeline breakage or distortion (from heat, weight of objects forced onto pipeline, or vibration)	Send out fire team
		Dispatch team to clear up objects onto pipeline
		Dispatch repair team
	Damages to pipeline facilities or infrastructure (from objects forced onto pipeline, vibration, heat, etc.)	Dispatch team to clear up objects onto pipeline
		Send out fire team
		Dispatch repair team

Snow

The need to monitor snow cover is important for several reasons. These include (Standley and Barrett, 1999):

- Snow has implications for human interaction (leisure, travel),
- Snow affects transportation (snow extent),
- Snow is a factor in flood prediction (water equivalent), and
- Snow is a factor in avalanche prediction (snow depth)

Meteorological weather systems for predicting snow precipitation have been developed and used for many years. This section will only address the technology of detecting snow cover and snow depth for transportation purposes. Visible and infrared radiometers can provide high spatial resolution maps of snow areas. But due to the occurrence of clouds, its usage is limited. A passive microwave (PM) radiometer, with its near all-weather capability, has been used widely in snow cover detection. Because of the crystals within the snow, the scattering of microwave radiation is different, thus making it easy to detect by PM sensors. Although PM imagery can provide near real time snow cover and snow depth data, conventional ground snow depth observations are still needed to calibrate and validate PM data (Kelly and Atkinson, 1999). The snow depth and ground elevation have strong associations. Thus geostatistical interpolation of DEMs and PM images can be used to estimate more accurate snow depth (Kelly and Atkinson, 1999). The PM imagery is not perfect because the discrimination of snow cover areas and precipitation cloud areas is sometimes doubtful. In order to distinguish between cloud top or snow cover on the ground, IR data can be added to detect temperature difference (Standley and Barrett, 1999). Generally speaking, in monitoring snow cover over large areas, it doesn't require high spatial resolution. Spatial resolutions equal or less than 1 km, and temporal resolutions equal to 1 day are sufficient.

In the beginning, the use of SAR to detect snow extent mainly relied on the difference in backscattering between snow and other ground objects. However, sometimes it is not so easy to discriminate between snow and ground objects just by backscattering value (Shi et al. 1997). Thu, Shi et al. (1997) use Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) multi-pass images, which have selectable spatial resolution from 10 to 200 meters, to detect the changes. This method has two main advantages: 1) it can detect both dry and wet snow, and 2) it doesn't require any topographic information.

For transportation use a higher spatial resolution is needed, e.g. it's hard to identify if a road segment has snow buildup on it using a 1 km spatial resolution image. Thus, airborne radar sensors such as the Danish EMISAR and ESAR are used to provide 2 m or better spatial resolution in detecting snow cover extent (Noll et al. 1996). Since modern remote sensing techniques have the capability to identify snow cover area and estimate snow depth. The combination of GIS and remote sensing images can provide near real time information to manage and control snowplowing and transportation routing.

Table 21. Snow and ice's impacts to roadway.

Impact	Cause	Activity
Block or close roadway	Presence of potential hazard	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
	Snow or ice buildup	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Set up temporary warning signal
		Dispatch snowplows
	Stranded vehicles on roadway (malfunction, stuck, etc)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch tow truck
Increase the probability of accidents occurring	Degradation in road surface conditions (slippery, soft shoulders or road (if dirt), etc)	Set up temporary warning signal
	Loss of traffic signals (loss of electric power)	Dispatch repair team
		Send out police officers
	Concealed or displaced traffic signs	Dispatch repair team
	Greater variation in traffic (speed, stopping on shoulders, etc)	Set up temporary warning signal
	Degradation in visibility (snow fall)	Set up temporary warning signal
	Congestion on roadway (evacuation, stranded vehicles, accidents, objects, etc)	Create alternative route(s)
		Send out police officers
		Dispatch tow truck

Table 22. Snow and ice's impacts to railway.

Impact	Cause	Activity
Block or close railway	Presence of potential hazard	Close railway
		Create alternative route(s)
		Inform train conductor of hazard location
		Scheduling
	Snow or ice buildup	Create alternative route(s)
		Inform train conductor of hazard location
		Scheduling
		Dispatch snowplows
	Stranded vehicles or train on railway (malfunction, derailment, etc.)	Close railway
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
		Evacuate passenger
		Dispatch ambulance and first-aid staff
		Dispatch tow truck
Increase the probability of accidents occurring	Degradation in road surface conditions (slippery, etc.)	Inform train conductor of hazard location
		Scheduling
	Loss of traffic signals or signs (loss of electric power)	Dispatch repair team
		Inform train conductor of hazard location
		Send out police officers
		Set up temporary warning signal
	Concealed traffic signs (from snow fall)	Inform train conductor of hazard location
	Degradation in visibility (snow fall)	Inform train conductor of hazard location

Table 23. Snow and ice’s impacts to pipelines.

Impact	Cause	Activities
Close the pipeline	Low temperature may congest pipeline	
Increase the probability of pipeline damage	Pipeline breakage or distortion (from cold temperature)	Dispatch repair team

Tornado

Tornados represent an on-going research area for many, but due to the rapid nature of the event no system can predict exactly when and where it will take place. With respect to post-event damage assessment, because tornados are usually accompanied by storms involving thick clouds and strong winds, using airborne remote sensing to acquire timely data can be dangerous. Spaceborne radar systems thus provide a promising safe method to assess post-event damages. The spatial and temporal resolution requirement of assessing ground damage is similar to those involved in the assessment of earthquakes. The acquisition of timely images between 6 and 48 hours after the event is recommended (Ozdogan and El-Baz, 2000). A spatial resolution of 2 m or better is required in assessing infrastructure damage. Higher spatial resolutions of 0.25 m are required to detect common objects that may be forced onto roadways by strong wind (Jensen and Cowen, 1999). However, most spaceborne systems can’t currently meet these technological requirements.

Since a tornado’s damage is often restricted to relatively small regions, roadway access is usually available to some degree after such events. Air and ground based surveys are the best way to assess such damages for now. However, as the technology progresses in the future, we may see increased use of spaceborne radar-based sensor systems for assessment of tornado damage.

Table 24. Tornado's impacts to roadway.

Impact	Cause	Activity
Block or close roadway due to:	Presence of potential hazard	Advertise Tornado warning
	Damage to roadway	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch repair team
	Debris forced onto roadway (from wind)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch team to clear up roadway
	Stranded vehicles on roadway (abandoned, transplanted, etc)	Close all or part of roadway (use barricade & signals as appropriate)
		Create alternative route(s)
		Dispatch tow truck
Increase the probability of accidents occurring due to:	Degradation in road surface conditions (slippery, soft shoulders or road, etc)	Set up temporary warning signal
	Debris forced onto roadway (from wind)	Dispatch team to clear up roadway
	Loss of traffic signals (missing or loss of electric power)	Dispatch repair team
		Send out police officers
	Missing traffic signs	Dispatch repair team
		Set up temporary warning signal
	Greater variation in traffic	Set up temporary warning signal
	Degradation in visibility (rain, etc.)	
	Congestion on roadway (evacuation, stranded vehicles, accidents, objects, etc)	Create alternative route(s)
		Dispatch team to clear up roadway
		Send out police officers
		Dispatch tow truck

* Tornado may induce storm

Table 25. Tornado's impacts to railway.

Impact	Cause	Activity
Block or close railway	Presence of potential hazard	Inform train conductor of hazard location
	Damage to railroad	Close all or part of railway
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
	Debris forced onto railroad (from wind)	Close all or part of railway
		Inform train conductor of hazard location
		Dispatch team to clear up railway
		Scheduling
	Stranded vehicles or locomotive on railway (abandoned, transplanted, derailment, etc.)	Close all or part of railway
		Dispatch repair team
		Inform train conductor of hazard location
		Scheduling
		Evacuate passenger
		Dispatch ambulance and first-aid staff
		Dispatch tow truck
Increase the probability of accidents	Degradation in railroad conditions (slippery, lost of ballast, etc.)	Dispatch repair team
		Inform train conductor of hazard location
	Debris forced onto railway (from wind)	Inform train conductor of hazard location
		Dispatch team to clear up railway
	Loss of traffic signals (missing or loss of electric power)	Dispatch repair team
		Inform train conductor of hazard location
		Send out police officers
		Set up temporary warning signal
	Missing traffic signs	Dispatch repair team
		Inform train conductor of hazard location
		Set up temporary warning signal
	Degradation in visibility (rain, etc.)	Inform train conductor of hazard location

* Tornado may induce storm.

Table 26. Tornado's impacts to pipelines.

Impact	Cause	Activities
Close the pipeline	Explosion of pipeline (from objects forced onto pipeline)	Cut off pipeline supply
		Sent out fire team
		Dispatch repair team
	Damages to pipeline (from vibration, objects forced onto pipeline)	Cut off pipeline supply
		Dispatch repair team
		Dispatch team to clear up objects onto pipeline
Increase the probability of pipeline damage	Pipeline breakage or distortion (from weight of objects forced onto pipeline, or vibration)	Dispatch team to clear up objects onto pipeline
		Dispatch repair team
	Damages to pipeline facilities or infrastructure (from objects forced onto pipeline, vibration, etc.)	Dispatch team to clear up objects onto pipeline
		Dispatch repair team

CHAPTER IV

TECHNOLOGICAL REQUIREMENTS OF REMOTE SENSING

This section explores the technological requirements for using remote sensing as a means for acquiring the information needed to detect and assess the causes for the various disaster/hazards presented in the previous section.

Debris on roadways and railway

It's always preferred to detect objects on the roadway as soon as possible. Since access to real-time images is not always possible, a temporal resolution of 5 to 60 minutes can provide reasonable performance (Jensen and Cowen, 1999). However, no spaceborne remote sensing system currently meets this temporal requirement and also provides the necessary spatial resolution as listed in Table 27. Geo-synchronous orbit satellites, such as GOES, can provide the necessary temporal resolution, but only provide spatial resolutions on the order of 1 km and can't cover all the areas needed. Jensen and Cowen (1999) identify two other methods that can provide 5 to 60 minute temporal resolution, (1) repetitive aerial photography (very costly), or (2) the placement of dedicated sensors on the top edge of buildings and posts to obtain oblique views. But both of these two methods are not capable of monitoring large areas and are easily compromised by bad weather. Therefore, in each of the cases discussed below involving the detection of debris, there is a need for access to a cost-effective source for imagery that possesses enhanced temporal resolution.

There are several types of objects that may commonly be deposited onto a roadway/railway as a result of the various disaster/hazards. Proposed technological needs for detecting each of these objects in terms of the temporal, spatial, and spectral resolutions are given in Table 27.

Table 27. Remote sensing requirements for detecting objects on the roadway.

Type of objects	**Temporal Resolution**	**Spatial Resolution**	**Spectral Resolution**
Tree	ASAP	~ 0.25 m	V-NIR
Rock	ASAP	~ 0.25 m	Pan-Radar
Vehicle	ASAP	~ 1 m	Pan-V
Mud	< 1 day	~ 1 m	Pan-V
Snow & Ice	< 1 day	~ 1 m	V-NIR-Passive microwave
Ash	< 1 day	~ 1 m	Pan-V
Lava	*	~ 30 m	Pan-V-NIR
Water	< 1 day	< 1 m	Pan-V-NIR-Radar
Building debris	ASAP	< 2 m	Pan-V-NIR-Radar-Lidar

* The temporal resolution of lava is depend on the location of occurrence of lava.

Tree and Rock

Trees and rocks are hard objects that may cause traffic accidents or damage to vehicles when encountered on roads and potential derailment when present on railways. The appearance of these objects also implies that there may be damage to the roadway/railway. Objects with a principal dimension greater than 0.5 meter are large enough to induce a traffic accident and thus should be removed from a roadway/railway as soon as possible. A spatial resolution of less than 0.25 meter is required to detect objects of this size (Jensen and Cowen, 1999). An ability to use this information to detect objects will contribute to ensuring the operational safety of roadway/railway transportation especially following an event that is likely to deposit objects onto a roadway/railway (e.g., floods, tornados, etc.).

To detect a tree or branch in a single image is easier than detecting a rock because the spectral signature of plants doesn't vary a lot between different species. Thus, if spatial and temporal resolution requirements are met, a multi-spectral or hyper-spectral remote sensing system should be effective in detecting wood on the roadway. In contrast, the spectral signature of rocks usually differs largely because the composition of rocks changes. Thus a multi-spectral sensor may not work efficiently unless the composition of rock of certain areas are known and constrained. The use of high spatial resolution multi-temporal images is currently more attractive for detecting changes on the roadway. So, if the spectral signature of a roadway is known, the use of high spatial resolution multi-temporal, multi-spectral or hyper-spectral sensors represents a promising technology when used with automatic differencing for object detection.

Since optical-based sensors are easily affected by weather conditions and not usable during the night, a radar image represents another source for use in detecting roadway objects. Because of the promising high spatial resolution of radar images, highly accurate DEMs derived from radar images make it possible to detect the sudden changes on the roadway, thus enabling the detection of objects. Using the difference between two DEMs may be easier for automatically identifying roadway objects. Airborne light detection and ranging (LIDAR) is another sensor that can generate high accuracy DEMs. Its potential high spatial resolution of 0.3 m and relative speed at generating DEMs makes it potentially suitable for this application. However, as mention above, temporal resolution is still a limitation.

Mud, snow, ice, and ash

Mud, snow, ice, and ash are small particles that may cover the roadway, and cause degradation on the roadway/railway surface possibly leading to an accident. When these coverings build up to a certain thickness, it may also prompt consideration of the closure of a roadway/railway. Accurate assessment of the location of such debris is important information for the coordination of activities to setup warning markers, as well as clean and clear such debris (e.g. snowplow dispatching and routing). Generally speaking, assuming that those objects will become potential hazards only when they cover at least half of the roadway, a spatial resolution of about 1 meter will be required to detect a patch size of 6 ft * 6 ft (based on a roadway width of 12 feet). Temporal resolution requirements vary among these objects. For snow and ice, a temporal resolution of a day is recommended for detection (Standley and Barrett, 1999). However, a temporal resolution of less than one day is more than likely necessary given that snow and ice may build up on the roadway/railway in a period shorter than a day. Mud and ash patches are most often associated with disaster events (flood, volcano, etc.) and will only require focused assessment within a confined area and the assessment can more than likely be scheduled.

Passive microwave, radar, and infrared sensors are widely used to detect snow and ice, because of their crystalline structure and thermal absorbing characteristic (Shi et al. 1997; Noll et al. 1996). Thus it should be no problem to utilize remote sensing techniques in transportation management if the spatial and temporal resolution matches with the need. For mud and ash, because their spectral signatures may be similar to the roadway, it's not easy to detect them from a single image. Given that multi-image differencing enhanced detection of water bodies (Takeuchi et al., 1999), this approach may be applicable to mud and ash as well.

Water

Water may cause slippery roadway conditions. Also, the appearance of standing water on the roadway may be indicative of additional damage underneath (e.g., potholes). Identifying the location and patch size is important for roadway maintenance and safety purposes. The appearance of a water pocket on the railroad track bed is another kind of hazard for railway transportation, and it will be discussed in the next section. The spatial and temporal resolution for detecting a water patch is similar to the requirements of detecting a snow patch. A water body is generally detected using near-infrared (NIR) bands because of its low backscattering characteristic. A problem with using an optical sensor in detecting water bodies is that the visible and NIR bands are easily affected by atmospheric conditions, surface reflection of sun light, and water turbidity. In order to avoid those disruption, Takeuchi et al. (1999) used Normalized Difference Vegetation Index (NDVI) computed from visible band and NIR band data of Landsat TM (NDVI = (NIR –RED) / (NIR + RED)). The reason for using NDVI in detecting a water body is that 1) its more stable in most conditions, and 2) the water reflectance is lower than other landcover types. The method mentioned above is used for detecting floods and we know the spatial resolution of Landsat TM is far below the required resolution for detecting objects on the roadway. However, it's a potential method when higher resolution optical sensors become available.

An active radar system is another potential method for detecting a water body. SAR backscatter on a calm water surface is the lowest level among different kinds of landcover types (Takeuchi et al. 1999). Although RADAR sensors have all weather capability and relative high spatial resolutions, it's sometimes difficult to distinguish between a water body and landcover just by backscatter in one image. Thus, Takeuchi et al. (1999) suggested using the difference between multi-temporal radar images for improved detection of water bodies.

Besides the patch size of a water body, its depth is another important factor to gauge its potential as a hazard. As the depth increases, its potential as a hazard increases. Water's spectral characteristics change when depth increases. Multispectral sensors of wavelength between 0.4 µm ~ 1.1 µm have different water penetration rates, and thus can be used to detect water depth (Belokon et al., 1997). But this method is only good for clear water, since water in the roadway puddles is always turbid. Turbid water has a different and complex spectral signature, thus, future work is needed to identify the proper remote sensing sensors to detect the depth of water bodies.

Lava

Lava has a heat radiation property that makes it easy to detect with an infrared channel. The heat sensitivity characteristic of infrared bands makes it easy to detect lava flow without high spatial resolution. Generally speaking, a spatial resolution of 30 meters or less will be sufficient. Since lava always appears in certain volcanic areas, the appearance of lava flow is always carefully monitored and it is possible to use this information in concert with roadway maps to establish the necessary actions for road closures.

Building Debris

Infrastructures damages are often found after a disaster event. Some disasters, such as earthquakes and landslides, may even cause buildings to collapse. Objects from the collapsed buildings or roadway infrastructures may fall on the transportation lines and thus become a potential hazard to traffic safety. Gamba and Casciati (1998) recommend that imagery with a spatial resolution of 2 m or less from both optical-based and radar-based, airborne or spaceborne, systems are useful for detecting building and other infrastructures damages. Also, the acquisition of timely images, between 6 to 48 hours after the event, is recommended (Ozdogan and El-Baz, 2000). Since high spatial resolution images are not always available during the 6 to 48 hours recommended period, moderate resolution optical-based images can be used to provide synoptic and large scale early assessment because the albedo value increases in damaged areas due to the exposed material and reduced shadow (Ozdogan and El-Baz, 2000).

Damage to Roadway/Railway

Providing timely information concerning roadway and railway damage is very important for ensuring transportation safety. However, timely images during or after a disaster are not always available. For example, bad weather may hamper the ability to obtain low-altitude images and thick clouds may restrict the use of optic-based high-altitude or space-based sensors. Even if timely images are available, the possibilities that a large variety of objects may be resting on the roadway will make it hard to identify and discern the damages to the infrastructure underneath. For example, during a flood, even an inch of water on the roadway will make it hard or near impossible to identify the presence of damage.

There are different kinds of roadway damage possible. Larger areas of damage that may result from such events as road openings and large cracks after an earthquake will require spatial resolutions on the order of 1-2 meters. Less severe damage, such as potholes that arise after flooding, will need higher spatial resolution images (0.25 ~ 0.5 m) for identification and assessment (Jensen and Cowen, 1999).

Soft shoulders are another hazard to transportation safety. Currently, not a lot of effort is spent on identifying soft shoulders since they usually do not cause serious damages. Soft shoulders are usually the result of accumulations of water or snow. Since the albedo value of wet road shoulders decrease in optical-based images, and the low backscattering in radar images, both optical-based and radar-based sensors are useful in this application. The width of a road shoulder varies, but the spatial resolution requirements for detecting soft shoulders are approximately the same as for detecting water patches on the roadway.

Given that railroads represent a principal source of transportation, it's important to maintain the integrity and safety of railway systems. Derailment is a prevalent disaster in railroad transportation. Common phenomena that may lead to derailment include track defects and a deteriorated track bed. Most common track defects are wide gage (a condition where the distance between the rails exceeds the allowable standards), defective switch points/track hardware at turnouts (Federal railroad administration, 2000). That's why derailment usually happens when a train passes a turnout (Miyamoto, 1996). Currently, a defective rail is detected by hand held or vehicle mounted sensors. These approach are costly and time consuming, and can not always be relied upon to provide timely information after a disastrous event. These sensors have a very high resolution (<1mm), which is required to detect a rail defect. Thus, given such accuracy requirements and the current state of remote sensing, this application will not be possible until major breakthroughs occur in sensor technology.

Erosion, lost of ballast, and water pockets are common problems associated with deteriorated track beds. These conditions usually cannot be detected by visual inspection, but can be associated with anomalous temperature changes along the track bed. Given that infrared sensors are sensitive to the thermal fluctuations and have proven useful in locating subsurface anomalies (Weil, 1995), it may be possible to make use of airborne or spaceborne infrared sensors for this application. The limitation of current infrared sensory information is that it can't provide depth information, which is very important in track bed maintenance. A ground penetrating radar system is currently coupled with an infrared sensor on single vehicle that traverses the track to provide depth information

(Weil, 1995). Airborne and spaceborne penetrating radar system are not currently available that can be used in this application.

Traffic load and flow speed

Traffic monitoring is of common interest for the purpose of short-term traffic management and long-term studies of traffic capacity. Monitoring is concerned with both the load on transportation routes as well as the speed of movement through those routes. These variables combine to define the congestion that a link is experiencing. A secondary effect of some disasters is traffic congestion. This congestion arises due to such events as evacuation, reductions in the number of available routes, weather conditions, etc. The onset of congestion represents a hazard that can lead to accidents and pose additional hazards. Therefore, it would be beneficial if congestion could be quickly detected at these times and remedied through various mechanisms (warnings, rerouting, signal manipulation, etc.). Thus there is a need for using remote sensing to acquire traffic flow and flow speed information.

Although remote sensing has been proposed to be useful for vehicle counting and possibly speed (Merry, 1996), one point of contention regarding its use in traditional studies is that it is unable to provide vehicle weight information for the purpose of roadway maintenance (Gardner, 2000). But, when used in the context of a disaster event, information such as traffic load and speed is of principle interest and no information concerning vehicle weight is needed.

Traffic load is calculated traditionally by counting vehicles either automatically or manually. Both of these methods suffer from accuracy and coverage problems, and are usually only employed for performing predefined scheduled assessments of heavy traffic segments (Kim et al., 1997). For automated counting, these assessments are performed using instruments permanently or temporarily located at the site. Due to the random occurrence and location of disasters, traditional methods are not likely to provide the timely information about really traffic conditions that would be needed for disaster related purposes. Some methods have been developed to calculate vehicle number from a single optical-based image (Gardner, 2000; Kim et al., 1997). But the application of those methods are still restricted mostly by the available spatial and temporal resolution of remote sensing images (not to mention the degradations that result with the use of these airborne or optic-based sensors in the presence of bad weather or thick clouds). There is a need to identify the potential use of spaceborne radar sensors in this application. Merry et al. (1996) used air-borne images in their study and stated that 1-meter spatial resolution is capable of counting and classifying vehicles with 90% accuracies. They are able to detect vehicle speed by taking two images within a short period, and tracking the spatial changes of a vehicle (Merry et al., 1996). This method is also useful in detecting stranded vehicles on the roadway, which may be caused by a disaster event, such as flood, earthquake, etc.

Once in place, the sensor based systems associated with the efforts of the Intelligent Transportation System (ITS) program should be able to provide the information needed in urban areas eliminating the need for air or space-based sensors to do the job. However, rural applications may still require the use of the non-standard approaches.

Damage to pipeline

There are various kinds of pipelines, such as gas pipeline, oil product pipeline, water pipeline, electricity line, sewer line, etc. Damage to a pipeline not only leads to loss of the contained resource, but may also threaten the safety of nearby persons or infrastructure. Table 28 lists the potential impacts to pipelines and their causes, as well as the activities that can help to reduce these impacts. The most common pipeline damage following a disaster is ruptures. Since the size of pipelines varies largely, as well as the scale of breakage, various spatial resolution are needed to detect the different possible ruptures that may result. In those cases where these has not been a disaster and persons are just interested in assessing the integrity of an exposed pipeline, a spatial resolution of less than 2 meters and a temporal resolution of approximately 4 months are recommended (Currie and Dechka, 1995). However, lower temporal resolutions are useable for post disaster assessment to assess such anomalies as breaks, leaks, etc. since the impact of these events results in detectable changes to the immediate environment on a larger scale.

Except for direct detection of pipeline breaks on exposed lines, which is traditionally performed regularly by visual observation, detection of gas or liquid leaks, which accompany pipeline ruptures, is another problem which is more suitable for using current remote sensing systems because it requires a lower spatial resolution. Leakage is usually hard to detect by traditional visual observation, but thermal plumes and heat loss that usually accompany pipeline leakage can be detected by thermal infrared. Such abnormal temperature changes along the pipeline are indicators that a pipeline segments is in need of maintenance. As for serious damages resulting in an explosion or flame, infrared bands are also useful. For oil product pipeline leakages, Lidar system has been proven to be able to detect problems accurately and quickly (Petuchov et al. 1999).

Table 28. Disaster/hazards' impacts to pipelines.

Impact	Cause	Activities
Close the pipeline	Explosion of pipeline (from heat, objects forced onto pipeline)	Cut off pipeline
		Sent out fire team
		Dispatch repair team
	Low temperature may congest pipeline	
	Damages to pipeline (from heat, vibration, objects forced onto pipeline)	Cut off pipeline
		Dispatch repair team
		Send out fire team
		Dispatch team to clear up objects onto pipeline
	Presence of potential hazard (flood, landslide, wildfire, volcano, etc.)	Cut off pipeline
Increase the probability of pipeline damage	Above ground lines being buried underground (from slide, earthquake, volcano, etc.)	Dispatch repair team
		Dispatch team to uncover the pipeline
	Pipeline breakage or distortion (from heat, cold temperature, weight of objects forced onto pipeline, or vibration)	Send out fire team
		Dispatch team to clear up objects onto pipeline
		Dispatch repair team
	Damages to pipeline facilities or infrastructure (from objects forced onto pipeline, vibration, heat, etc.)	Dispatch team to clear up objects onto pipeline
		Send out fire team
		Dispatch repair team

As for underground pipelines, traditional methods include 1) using "crawl crews" or other visual inspection means, and 2) taking samples by sounding or boring at certain pipeline segment. These methods are dangerous, time consuming, costly, and not accurate. Weil (1992, 1995) proposed the using of infrared thermography to identify the underground pipeline damages. By coupling this sensor with ground penetrating radar, it has been proved that location and depth of damaged pipelines can be detected accurately and successfully. However, these sensors are currently used in the form of either hand-held or vehicle-mounted instruments. There is a need to explore the potential to enhance such systems for airborne or spaceborne use.

Distortion of a pipeline is a hazard in that it represents a potential increase in stress in a pipeline that may result in a break or rupture in the future. Such distortions may be detectable using high spatial resolution remote sensing sensors (both optical- and radar-based). However, given that pipeline size may vary, different spatial resolutions are needed. Generally speaking a spatial resolution of 1 meter or less is sufficient (Herb et al., 1996).

Presence of potential hazard

The phrase "presence of potential hazard" appears in Tables 2 through 26 as a common cause for many impacts of the disasters. The presence of a potential hazard indicates that conditions exist for the creation of one or more hazards which themselves may lead to a disaster or worsen the impact of the current one. This cause was included in this study to ensure that persons consider these potential hazards when performing an assessment of an area in association with a disaster. However, for each type of disaster, there are many conditions that may fit this situation, and for each a different set of remote sensing requirements may exist. As well, there may be many different methods available to predict or assess the same disaster. For example, volcanic eruptions can be predicted by monitoring the ground elevation changes and abnormal temperature changes. Table 29 lists the data that may be used to help predict a disaster. Note that even if all the data are available, no one can be totally sure where and when a disaster will take place, because predicting a disaster is often a complex function involving several of the factors shown in the table.

Table 29. Data required for predicting potential hazard.

Flood	Cloud type, temperature, topology, runoff model, water levels, ground cover, Land use pattern, Ground surface elevation, ground surface gradient, soil type, precipitation amount, runoff model, tidal level, atmospheric conditions,
Snow and ice	Atmospheric conditions, Cloud type, temperature, snow extend, snow depth, topography
Wildfire	Location and trend of fire, soil moisture, wind, temperature, vegetation condition
Landslide	Land cover, slope, soil moisture, depreciation, soil density
Volcano	Topography, soil deformation, temperature, the forming of lava dome

Predicting a potential hazard is important in disaster management as well as in transportation. The presence of a potential disaster may lead to road closure, rerouting, as well as the execution of evaluation and prevention activities. Some disasters are predictable but due to the current technology limitation, these applications are restricted because of the poor accuracy of available information or the lack of enough time to prepare. For example, a tsunami warning system has been used for more than 50 years, but the warning time of a tsunami is usually less than 1 hour (Ministry of Attorney General, 1995). This is rarely sufficient time to make the necessary arrangements to properly address safety concerns. An earthquake is predictable, but giving the poor accuracy in being able to specify nothing more than a range of possible time within which it may occur (i.e., next month), nothing can effectively be done during such a warning period.

In addition to their use in prediction of the onset of a disaster, information concerning these factors can also be used in the case of slower disasters, such as wildfires and floods, to provide important data for use in modeling the movement of the disaster so strategists can make plans to issue warnings to those areas in the potential path of the disaster. To support such efforts, there is a need to integrate prediction and modeling tools that make use of a variety of data sources (terrestrial, air-borne, and space-borne) to provide the relevant information concerning a disaster that planners can use to aid in their decision making duties.

Damaged traffic signs and signals

Traffic signs and signals are vital elements for ensuring the safety of transportation. It is possible that a disastrous event may cause the malfunction, displacement, and/or concealment of one or more traffic signs or signals. Research involving the use of remote sensing to do roadside inventory may be applicable for detecting these problems. However, the spatial resolution requirements would be extreme and require careful documentation of the desired position of all existing signs and signals. As for the detection of malfunctioning signals, such as from a loss of electricity, these anomalies would be easier detected through the use of terrestrial sensors and many such reporting systems will be available as a part of the ITS initiative.

Given the high spatial resolution requirement (< 0.1 m) for detecting the signs and signals damages, most of the current sensors available are not applicable. However, Lidar has been used to detect the integrity of power transmission lines (Al-Turk and Uddin, 1999). With its high spatial resolution, Lidar may be a potential sensor for this application. Another possible application to explore may be the use of low oblique sensor views to detect damaged signs, since a low oblique view will reduce the spatial requirements.

Degradation in visibility

Degradation in driving visibility in the presence of rain, snow, fog, or heavy smoke is not only a hazard that may lead to traffic accidents, but it can also cause traffic congestion due to the associated voluntary reduction in traffic speed. There is not much that can be done to change nature; therefore, the interest is in detecting these events to afford opportunities for providing drivers with weather forecasts or warnings and to direct crews to take measures to reduce the hazard (e.g., salting roads, erecting warning signs, etc.), close roads, and reroute traffic. Rain and snow detection is currently handled by various kinds of sensors, such as Doppler radar systems and spaceborne optical-based sensors. Rain, snow, and fog are predictable by well-built weather forecasting systems that have been used for many years. Information is easily accessed via various kinds of media. Smoke, usually covers a large area and does not require high spatial resolution to detect it.

Summary

As seen from the discussion in this section, the technological factors that limit the potential applications involving remote sensing entail one or more constraints in terms of the ability of the available sensor systems to provide the required spatial, temporal, and/or spectral resolution. Future research is needed to develop sensor systems and processing methods that overcome these limitations. When available these systems will then need to be matched with the potential applications presented and deployed.

As well, the activities outlined in Tables 2 through 26, e.g., devising new routes, deciding on road closures, effecting an evacuation, etc., need a composite of information from various sources. Decision systems need to be developed that aid in processing and properly presenting to the user the relevant information gathered from the fusion of remote sensor data and possibly other data (terrestrial sensors).

CHAPTER V

PROPOSED RESEARCH AGENDA

Based on a review of the research presented and the needs identified in Sections 3 and 4, a table was created that summarizes the general research needs required to support continuing growth in the use of remote sensing in the predication and assessment of hazards and disasters. These needs are listed in Table 30. The identified research needs encompass research in both the development and enhancement of existing sensor technologies as well as methods of processing collected data.

Table 30. Level 1 Research Items.

1. Development of decision systems to aid in processing and properly presenting to the user the relevant information gathered from the fusion of remote sensor data and possibly other data (terrestrial sensors) for the purpose of performing the activities outlined in Tables 2 through 26 (e.g., devising new routes, deciding on road closures, effecting an evacuation, etc.).
2. Enhance the ability of remote systems to provide timely, accurate predictions of earthquakes.
3. Enhance the ability of remote systems to provide timely, accurate detection and identification on roadways/railways.
4. Develop or enhance existing processing methods for using sensor information to assess the extent of damages resulting from disasters. This includes assessment of damage to both infrastructure and the environment.
5. Enhance the ability of remote systems to provide timely, accurate detection and identification of defects and damage to above- and underground pipelines.
6. Develop or enhance existing methods and tools for using sensor information to predict the propagation of slow moving disasters such as flooding.

Given that the items shown in Table 30 represent general research needs, we felt it was necessary to provide additional details concerning the needs of item number 3 in the list. These additional details are given to provide a better understanding of the research needs in this area. These needs are defined as level 2 items (numbered 3.x in Table 31), with the further detailed breakdown defined as level 3 items (numbered 3.x.x in Table 31). These labels are needed to support discussion in the section that follows.

Table 31. Level 2 and Level 3 Research Items.

3.1 Congestion (traffic flow and speed, stranded vehicles)
3.2 Infrastructure (road, track, bridge, etc.) defects and damage.
    3.2.1 Particularly in the presence of varying levels of floodwater.
    3.2.2 Infrastructure for roadways includes: road, surface, shoulders, bridges, etc.
    3.2.3 Infrastructure for railways includes: rails, track beds, etc.
3.3 Hazardous driving conditions
    3.1.1 Buildup of water, mud, ash, snow and ice.
    3.1.2 Low visibility conditions (e.g. fog, smoke, heavy rain, blizzard, etc.)
    3.1.3 Soft shoulders.
3.4 Damaged, missing, or accidentally relocated traffic signs or signals.
3.5 Foreign objects (tree, rocks, lava, building debris, etc.)

Ranking of the Research Needs

In order to help provide direction with respect to the prescribed research agenda, we believed it would be beneficial to rank these needs. The Analytic Hierarchy Process (AHP) (Saaty, 1982) was chosen because it provides a way to rank the agenda items by only having to make pairwise comparisons for each of the different criteria. These comparisons rely on users selecting a value on a scale from 1 to 9 with designations for the scores being “1 - equally preferred”, “2 – equally to moderately preferred”, … “8 –

very to extremely strongly preferred," and "9 – extremely preferred". Also given the small number of items in the list, use of AHP would not result in the need to process too many comparisons making the process of ranking the alternative relatively easy and straightforward.

To rank the list of research items requires that criteria be defined for the basis of the ranking. The following criteria were selected.

1. The impact that research in this area would have on transportation. Specifically with respect to (1) the reduction in money lost due to disasters, and (2) the resulting improvements in transportation safety.
2. The cost of remote sensing, which is a function of the spatial, spectral and temporal resolution requirements required of the application.

It is realized that specific sensor type (e.g., infrared, passive-microwave, Lidar, etc.) and the required preprocessing are also important factors that influence the cost of remote sensing images. But since it may be possible to use one or more sensor types to accomplish the same task for a particular identified research need, it would be hard to include "sensor type" as one of the criteria in that it would be necessary to list and evaluate each. As well, a majority of the preprocessing of remote sensing images is often performed by the image providers and included in the total cost of obtaining the image, or the amount and cost of processing is a function of the specific application and difficult to determine at this point. Therefore, both of these factors were not specifically considered in the evaluation. Availability of data from remote sensing is another possible criteria for ranking the items in the agenda. However, giving that each research need may use different sensors and different techniques to support its needs, performing a comparison becomes too tedious. In addition, availability of data has a close relationship with the existing "cost of remote sensing" criterion. Another possible criterion is the improvements that result from employment of the new method over existing methods. However, it would be hard for us in this study to determine these relationships. Readers are reminded that independent of the criteria used, the AHP method can easily be applied using their own set of criteria using the method outlined in Appendix A.

The items listed in the agenda at Level 1 focus principally on software development and the use and integration of various sources of data. Therefore, the second criterion "cost of remote sensing" is not suitable because one would have to take into consideration and rank all the specific remote sensing sources possible. Thus, only the first criterion is used, e.g. impact to transportation. Since there are two sub-criteria in the first criterion, e.g. "improve safety" and "reduce money lost". The process of using AHP to rank level 1 agenda items requires first ranking the priorities of these two criteria. In our analysis, these two sub-criteria were deemed to have equal priority.

Next the actual level 1 items in the list were ranked separately according to each criteria "improve safety" and "reduction in money lost". Table 32 and Table 33 show the results of the pairwise comparison of level 1 agenda items for each of the criterion. In these tables the headings for the rows and columns represent the numbers associated with the level 1items in Table 30. The entries are the score assigned by the person performing the ranking. For example, the entry for row 2, column 1 states that in terms of improving transportation safety item 2 is four times more important than item 1. The entry for row 1 column 2 is then just the inverse of this score (1/4 or 0.25 in this case).

Table 32. Level 1 pairwise comparison using the criterion - "improve safety".

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	Result
No. 1	1	4	0.5	2	6	3	0.261
No. 2	0.25	1	0.25	0.5	4	1	0.095
No. 3	2	4	1	3	6	3	0.356
No. 4	0.5	2	0.333	1	5	2	0.158
No. 5	0.167	0.25	0.167	0.2	1	0.5	0.040
No. 6	0.333	1	0.333	0.5	2	1	0.089
Total	4.25	12.25	2.583	7.2	24	10.5	1

Table 33. Level 1 pairwise comparison using the criterion - "reduction in money lost due to disaster".

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	Result
No. 1	1	0.333	1	3	4	2	0.182
No. 2	3	1	0.5	4	6	5	0.305
No. 3	1	2	1	6	7	2	0.309
No. 4	0.333	0.25	0.167	1	2	1	0.068
No. 5	0.25	0.167	0.143	0.5	1	2	0.060
No. 6	0.5	0.2	0.5	1	0.5	1	0.075
Total	6.083	3.95	3.31	15.5	20.5	13	1

Using the priorities of criteria and priorities of agenda items, AHP permits us to calculate the final priorities of agenda items. The results are shown in Table 34.

The level 2 agenda items are more focused on certain phenomena that can actually be monitored and detected by certain remote sensing sensors. Therefore, both criteria, impact and cost, are used to rank these agenda items. The detail of AHP process of level 2 ranking is referred to Appendix. Level 3 items in the agenda are not ranked, but included to provide additional detail to the agenda.

Table 34. Resulting priority of level 1 agenda items.

Item	AHP Score
No. 1	0.222
No. 2	0.200
No. 3	0.333
No. 4	0.113
No. 5	0.050
No. 6	0.082

Results of Ranking

The final ranking of the research items represent the proposed research agenda and is shown in Table 35. The six items listed at Level 1 indicate the preferences based on the potential that research in these areas could have on improving transportation safety and reducing the money lost due to the occurrence of such related disastrous events. The five sub-items listed below the first Level 1 item indicate the ranking taking into account remote sensing cost. This would indicate that applications aimed at “hazardous driving condition” would be cheaper to implement and at the same time improve transportation safety. “Infrastructure defects and damages” is important to transportation safety, however, it usually require higher spatial resolutions that are harder and more costly to acquire. “Congestion”, “foreign objects”, and “damaged, missing traffic signs or signals” pose less threat to transportation safety and they do not usually result in a substantial loss of money.

The second Level 1 item in the proposed research agenda, “Development of decision systems to aid in processing and properly presenting to the user the relevant information gathered from the fusion of remote sensor data,” is another important need that has been under development by various departments. This application still needs more effort to provide the right information to the right person who needs it. The third item, “Enhance the ability of remote sensing systems to provide timely, accurate predictions of earthquakes,” is of critical importance in certain geographic areas. Current techniques of predicting an earthquake are not accurate enough to provide any helpful warning, thus more efforts are needed in this area. The fourth item, “Develop or enhance existing processing methods for using sensor information to assess the extent of damages resulting from disasters," includes using various kind of remote sensing sensors, e.g. visible, infrared, radar, etc., to assess the damages caused by all kinds of disasters. This task has been of interest for various purposes for many years. But with the invention of new sensors and software, future work is still needed. The fifth item, "Develop or enhance existing methods and tools for using sensor information to predict the propagation of slow moving disasters," is a very difficult task because the occurrence of a disaster is a complex function dependent on a range of factors. Progress in this area will largely improve the safety of transportation and society as a whole. The last item on the agenda, "Enhance the ability of remote systems to provide timely, accurate detection and identification of defects and damage to above- and underground pipelines," emphasizes continued development of airborne and space borne sensors. Several sensors used today are limited to ground use due to such issues as sensitivity and noise, and therefore are laborious to use over long lengths. By shifting from ground sensors to airborne or space borne sensors will increase the coverage and provide cheaper methods of monitoring the integrity of pipeline networks. The ranking of the items in the research agenda is a function of the ratings assigned in the pairwise comparison. Given the subjective nature of this scoring exercise, it is advisable for those interested to perform their own ranking. The complete analysis via AHP is provided in the Appendix for illustration and to provide an understanding of the values assigned subjectively that resulted in the ranking shown in Table 35.

Table 35. Research agenda.

- Enhance the ability of remote systems to provide timely, accurate detection and identification on roadways/railways of:
    - Hazardous driving conditions
        - Buildup of water, mud, ash, snow and ice.
    - Low visibility conditions (e.g. fog, smoke, heavy rain, blizzard, etc.)
    - Soft shoulders.
    - Infrastructure (road, track, bridge, etc.) defects and damage.
        - Particularly in the presence of varying levels of floodwater.
        - Infrastructure for roadways includes: road, surface, shoulders, bridges, etc.
        - Infrastructure for railways includes: rails, track beds, etc.
    - Congestion (traffic flow and speed, stranded vehicles)
    - Foreign objects (tree, rocks, lava, building debris, etc.)
    - Damaged, missing, or accidentally relocated traffic signs or signals.
- Development of decision systems to aid in processing and properly presenting to the user the relevant information gathered from the fusion of remote sensor data and possibly other data (terrestrial sensors) for the purpose of performing the activities outlined in Tables 2 through 17 (e.g., devising new routes, deciding on road closures, effecting an evacuation, etc.).
- Enhance the ability of remote systems to provide timely, accurate predictions of earthquakes.
- Develop or enhance existing processing methods for using sensor information to assess the extent of damages resulting from disasters. This includes assessment of damage to both infrastructure and the environment.
- Develop or enhance existing methods and tools for using sensor information to predict the propagation of slow moving disasters such as flooding.
- Enhance the ability of remote systems to provide timely, accurate detection and identification of defects and damage to above- and underground pipelines.

Notation: • = Level 1; ○ = Level 2; ■ = Level 3

CHAPTER VI
CONCLUSION

The goal of this study was to develop a research agenda that identifies areas of research that need to be addressed to enhance the application of remote sensing to the assessment of hazards, safety, and disasters which impact transportation. Remote sensing has been used for more than 50 years in various areas. But as for its application to this domain of transportation, it's still a relatively young technology. However, remote sensing has the potential capability to provide the information that can increase the operation and safety of transportation.

In order to devise a future research agenda, the current state of the research in this area was identified. The disaster/hazards that have critical impacts on transportation domain were first identified (shown in Table 1) and then potential impacts of each disaster/hazard were defined (Tables 2 through 26) and activities that might reduce or prevent these impacts listed. Based on these findings, the information requirements posed by these activities were defined and discussed for each phenomenon, e.g. debris on the roadway, damages to pipeline, etc. This resulted in a list of potential research items that were categorized and ranked using the Analytical Hierarchy Process (see Table 35). This agenda represents a proposal of what directions need to be taken to advance the research in the area of applying remote sensing to hazard, safety, and disaster assessment.

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APPENDIX

AHP RANKING PROCESSES

Criteria

Two criteria are used to rank the items in the research agenda, they are:

1. The impact that research in this area would have on transportation. Specifically with respect to (1) the reduction in money lost due to disasters, and (2) the resulting improvements in transportation safety.
2. The cost of remote sensing, which is a function of the spatial, spectral and temporal resolution requirements required of the application

Level 1 AHP ranking process

For ranking level 1 items (see listing in Table 30), only the first criteria is used. Thus, the first step is to weight its sub-criteria: "reduce money lost" and "improve safety". These two sub-criteria are assigned the same weight on "the impact that research in this area would have on transportation", so a unit weight is given to comply with AHP's definition that a value of 1 indicates "equally preferred".

Table A.1. Comparison of "improve safety" and "reduce money lost".

	Improve Safety	Reduce money lost
Improve Safety	1	1
Reduce money lost	1	1
Total	2	2

These weights are then normalized so that the sum of each criterion becomes 1. After normalization, the result of above table becomes:

Table A.2. Result after normalization.

	Improve Safety	Reduce money lost
Improve Safety	0.5	0.5
Reduce money lost	0.5	0.5
Total	1	1

Thus the resulting priorities are:

Improve safety: (0.5+0.5)/2 = 0.5

Reduce money lost: (0.5+0.5)/2 = 0.5

The second step is to perform a pairwise comparison between each item for each of the two criteria "improve transportation safety" and "reduce money lost due to disaster". For example, the entry for row 2, column 1 in the table below, states that in terms of improving transportation safety, item 2 is four times more important than item 1. The entry for row 1 column 2 is then just the inverse of this score (1/4 or 0.25 in this case) indicating that item 1 is four time less important. After completing the pairwise comparisons, the next step is to normalize the entries in each column of the table. The results are as shown in the following two tables.

Criterion: Improve transportation safety

Table A.3. Level 1 comparison according to criterion “improve transportation safety”.

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
No. 1	1	4	0.5	2	6	3
No. 2	0.25	1	0.25	0.5	4	1
No. 3	2	4	1	3	6	3
No. 4	0.5	2	0.333	1	5	2
No. 5	0.167	0.25	0.167	0.2	1	0.5
No. 6	0.333	1	0.333	0.5	2	1
Total	4.25	12.25	2.583	7.2	24	10.5

Table A.4. Normalization of level 1 comparison according to criterion “improve transportation safety”.

	No. 1	No.2	No. 3	No. 4	No. 5	No. 6
No. 1	0.235	0.327	0.194	0.278	0.250	0.286
No. 2	0.059	0.082	0.097	0.069	0.167	0.095
No. 3	0.471	0.327	0.387	0.417	0.250	0.286
No. 4	0.118	0.163	0.129	0.139	0.208	0.190
No. 5	0.039	0.020	0.065	0.028	0.042	0.048
No. 6	0.078	0.082	0.129	0.069	0.083	0.095
Total	1.000	1.000	1.000	1.000	1.000	1.000

The resulting priority for each row according to criterion “improve transportation safety” is then computed as:

No. 1: (0.235+0.327+0.194+0.278+0.250+0.286)/6 = 0.261

No. 2: (0.059+0.082+0.097+0.069+0.167+0.095)/6 = 0.095

No. 3: (0.471+0.327+0.387+0.417+0.250+0.286)/6 = 0.356

No.4: (0.118+0.163+0.129+0.139+0.208+0.190)/6 = 0.158

No. 5: (0.039+0.020+0.065+0.028+0.042+0.048)/6 = 0.040

No. 6: (0.078+0.082+0.129+0.069+0.083+0.095)/6 = 0.089

Criterion: Reduce money lost due to disaster

Table A. 5. Level a comparison according to criterion “reduce money lost due to disaster”.

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
No. 1	1	0.333	1	3	4	2
No. 2	3	1	0.5	4	6	5
No. 3	1	2	1	6	7	2
No. 4	0.333	0.25	0.167	1	2	1
No. 5	0.25	0.167	0.143	0.5	1	2
No. 6	0.5	0.2	0.5	1	0.5	1
Total	6.083	3.95	3.31	15.5	20.5	13

Table A.6. Normalization of level 2 comparison according to criterion “reduce money lost due to disaster”.

	No. 1	No.2	No. 3	No. 4	No. 5	No. 6
No. 1	0.164	0.084	0.302	0.194	0.195	0.154
No. 2	0.493	0.253	0.151	0.258	0.293	0.385
No. 3	0.164	0.506	0.302	0.387	0.341	0.154
No. 4	0.055	0.063	0.050	0.065	0.098	0.077
No. 5	0.041	0.042	0.043	0.032	0.049	0.154
No. 6	0.082	0.051	0.151	0.065	0.024	0.077
Total	1.000	1.000	1.000	1.000	1.000	1.000

The result priorities according to criterion “reduce money lost due to disaster” is then:

No. 1: (0.164+0.084+0.302+0.194+0.195+0.154)/6 = 0.182

No. 2: (0.493+0.253+0.151+0.258+0.293+0.385)/6 = 0.305

No. 3: (0.164+0.506+0.302+0.387+0.341+0.154)/6 = 0.309

No. 4: (0.055+0.063+0.050+0.065+0.098+0.077)/6 = 0.068

No. 5: (0.041+0.042+0.043+0.032+0.049+0.154)/6 = 0.060

No. 6: (0.082+0.051+0.151+0.065+0.024+0.077)/6 = 0.075

Level 1 items ranking

Using the derived priorities from the evaluation of both criteria above and the weighting assigned for each criterion, the ranking for the priority of level 1 items is:

No. 1: 0.5*0.261 + 0.5*0.182 = 0.222

No. 2: 0.5*0.095 + 0.5*0.305 = 0.200

No. 3: 0.5*0.356 + 0.5*0.309 = 0.333

No. 4: 0.5*0.158 + 0.5*0.068 = 0.113

No. 5: 0.5*0.040 + 0.5*0.060 = 0.050

No. 6: 0.5*0.089 + 0.5*0.075 = 0.082

Level 2 AHP ranking process

Both criteria, e.g. “cost of image” and “impact to transportation”, are used to rank level 2 items. Thus as before, the first step is to weight these two criteria and then normalize the weighting.

Table A.7. Pairwise comparison of “cost of image” and “impact to transportation”.

	Cost of image	Impact to transportation
Cost of image	1	0.25
Impact to transportation	4	1
Total	5	1.25

Table A.8. Normalization of pairwise comparison of “cost of image” and “impact to transportation”.

	Cost of image	Impact to transportation
Cost of image	0.2	0.2
Impact to transportation	0.8	0.8
Total	1	1

Thus the resulting priorities are:

Cost of image: (0.2+0.2)/2 = 0.2

Impact to transportation: (0.8+0.8)/2 = 0.8

The second step is to compare weight the sub-criteria of each criterion, e.g. compare “improve to safety” vs. “reduce money lost”, and compare “spatial resolution requirement”, “temporal resolution requirement”, vs. “spectral resolution requirement”. The pairwise comparison and results after normalization are:

Table A.9. Pairwise comparison of sub-criteria under "impact to transportation".

	Improve Safety	Reduce money lost	Priority
Improve Safety	1	1	0.5
Reduce money lost	1	1	0.5
Total	2	2	1

Table A.10. Pairwise comparison of sub-criteria under "cost of image".

	Spatial resolution requirement	Temporal resolution requirement	Spectral resolution requirement
Spatial resolution requirement	1	6	8
Temporal resolution requirement	0.167	1	6
Spectral resolution requirement	0.125	0.167	1
Total	1.292	7.167	15

Table A.11. Normalization of pairwise comparison of sub-criteria under "cost of image".

	Spatial resolution requirement	Temporal resolution requirement	Spectral resolution requirement
Spatial resolution requirement	0.774	0.837	0.533
Temporal resolution requirement	0.129	0.140	0.400
Spectral resolution requirement	0.097	0.023	0.067
Total	1.000	1.000	1.000

The resulting priorities are then computed as:

Spatial resolution requirement: (0.774+0.837+0.533)/3 = 0.715

Temporal resolution requirement: (0.129+0.140+0.400)/3 = 0.223

Spectral resolution requirement: (0.091+0.023+0.067)/3 = 0.062

After comparing both criteria and their sub-criteria, the next step is to pairwise compare level 2 items (as listed in Table 31) according to each sub-criterion. The following tables show the pairwise comparison and results after normalization.

Criterion: Spatial resolution requirement

Table A.12. Level 2 item comparison according to “spatial resolution requirement”.

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5
No. 3.1	1	3	0.25	4	3
No. 3.2	0.333	1	0.167	2	0.5
No. 3.3	4	6	1	8	6
No. 3.4	0.25	0.5	0.125	1	0.5
No. 3.5	0.333	2	0.167	2	1
Total	5.917	12.5	1.708	17	11

Table A.13. Normalization of level 2 item comparison according to “spatial resolution requirement”.

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5
No. 3.1	0.169	0.240	0.146	0.235	0.273
No. 3.2	0.056	0.080	0.098	0.118	0.045
No. 3.3	0.676	0.480	0.585	0.471	0.545
No. 3.4	0.042	0.040	0.073	0.059	0.045
No. 3.5	0.056	0.160	0.098	0.118	0.091
Total	1.000	1.000	1.001	1.000	1.000

The resulting priorities of level 2 items according to “spatial resolution requirement” are then:

No. 3.1: (0.169+0.240+0.146+0.235+0.273)/5 = 0.213

No. 3.2: (0.056+0.080+0.098+0.118+0.045)/5 = 0.079

No. 3.3: (0.676+0.480+0.585+0.471+0.545)/5 = 0.551

No. 3.4: (0.042+0.040+0.073+0.059+0.075)/5 = 0.052

No. 3.5: (0.056+0.160+0.098+0.118+0.091)/5 = 0.105

Criterion: Temporal resolution requirement

Table A.14. Level 2 item comparison according to “temporal resolution requirement”.

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5
No. 3.1	1	4	0.5	0.125	1
No. 3.2	0.25	1	4	0.5	7
No. 3.3	2	0.25	1	0.25	8
No. 3.4	8	2	4	1	9
No. 3.5	1	0.143	0.125	0.111	1
Total	12.25	7.393	9.625	1.986	26

Table A.15. Normalization and calculation of priorities for level 2 item comparisons according to “temporal resolution requirement”.

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5	Priority
No. 3.1	0.082	0.541	0.052	0.063	0.038	0.155
No. 3.2	0.020	0.135	0.416	0.252	0.269	0.218
No. 3.3	0.163	0.034	0.104	0.126	0.308	0.147
No. 3.4	0.653	0.271	0.416	0.504	0.346	0.438
No. 3.5	0.082	0.019	0.013	0.056	0.038	0.042
Total	1.000	1.000	1.000	1.000	1.000	1

Criterion: Spectral resolution requirement

Table A.16. Level 2 item comparison according to "spectral resolution requirement".

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5
No. 3.1	1	1	0.5	2	4
No. 3.2	1	1	1	2	3
No. 3.3	2	1	1	3	4
No. 3.4	0.5	0.5	0.333	1	2
No. 3.5	0.25	0.333	0.25	0.5	1
Total	4.75	3.833	3.083	8.5	14

Table A.17. Normalization and calculation of priorities for level 2 item comparisons according to "spectral resolution requirement".

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5	Priority
No. 3.1	0.211	0.261	0.162	0.235	0.286	0.231
No. 3.2	0.211	0.261	0.324	0.235	0.214	0.249
No. 3.3	0.421	0.261	0.324	0.353	0.286	0.329
No. 3.4	0.105	0.130	0.108	0.118	0.143	0.121
No. 3.5	0.053	0.087	0.081	0.059	0.071	0.070
Total	1.000	1.000	1.000	1.000	1.000	1

Criterion: Improve transportation safety

Table A.18. Level 2 item comparison according to "improve transportation safety".

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5
No. 3.1	1	2	1	3	2
No. 3.2	0.5	1	0.333	3	1
No. 3.3	1	3	1	2	3
No. 3.4	0.333	0.333	0.5	1	1
No. 3.5	0.5	1	0.333	1	1
Total	3.333	7.333	3.167	10	8

Table A.19. Normalization and calculation of priorities for level 2 item comparisons according to "improve transportation safety".

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5	Priority
No. 3.1	0.300	0.273	0.316	0.300	0.250	0.288
No. 3.2	0.150	0.136	0.105	0.300	0.125	0.163
No. 3.3	0.300	0.409	0.316	0.200	0.375	0.320
No. 3.4	0.100	0.045	0.158	0.100	0.125	0.106
No. 3.5	0.150	0.136	0.105	0.100	0.125	0.123
Total	1.000	1.000	1.000	1.000	1.000	1

Criterion: reduce money lost

Table A.20. Level 2 item comparison according to "reduce money lost".

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5
No. 3.1	1	0.333	1	0.5	0.333
No. 3.2	3	1	3	3	1
No. 3.3	1	0.333	1	2	2
No. 3.4	2	0.333	0.5	1	0.333
No. 3.5	3	1	0.5	3	1
Total	10	3	6	9.5	4.667

Table A.21. Normalization and calculation of priorities for level 2 item comparisons according to "reduce money lost".

	No. 3.1	No. 3.2	No. 3.3	No. 3.4	No. 3.5	Priority
No. 3.1	0.100	0.111	0.167	0.053	0.071	0.100
No. 3.2	0.300	0.333	0.500	0.316	0.214	0.333
No. 3.3	0.100	0.111	0.167	0.211	0.429	0.203
No. 3.4	0.200	0.111	0.083	0.105	0.071	0.114
No. 3.5	0.300	0.333	0.083	0.316	0.214	0.249
Total	1.000	1.000	1.000	1.000	1.000	1

Level 2 items result priorities

According to the results from the above three tables, the final ranking of Level 2 items is obtained from the following calculations.

No. 3.1: 0.2*(0.715*0.213 + 0.223*0.155 + 0.062*0.231) + 0.8*(0.5*0.288 + 0.5*0.100) = 0.195

No. 3.2: 0.2*(0.715*0.079 + 0.223*0.218 + 0.062*0.249) + 0.8*(0.5*0.163 + 0.5*0.333) = 0.223

No. 3.3: 0.2*(0.715*0.551 + 0.223*0.147 + 0.062*0.329) + 0.8*(0.5*0.320 + 0.5*0.203) = 0.299

No. 3.4: 0.2*(0.715*0.052 + 0.223*0.438 + 0.062*0.121) + 0.8*(0.5*0.106 + 0.5*0.114) = 0.116

No. 3.5: 0.2*(0.715*0.104 + 0.223*0.042 + 0.062*0.070) + 0.8*(0.5*0.123 + 0.5*0.249) = 0.167