- Roadside Central Computer: The roadside central computer must be portable and rugged so that it can withstand the frequent relocation that may be required due to the temporary nature of work zones. It will house the software required to carry out the operations essential for the working of the system. The roadside central computer may or may not make decisions on the status of traffic and the nature of messages to be displayed, depending on the decision to include a traffic control center in the loop. The computer may be either UNIX , DOS , or Windows-based, and should be connected to the data collection devices, traffic control center, and information dissemination devices via suitable communication links. Finally, the roadside central computer may be automatic or can be monitored by trained traffic personnel.

- Information Dissemination Devices: The system should employ appropriate information dissemination/output devices that are available to the majority of the traffic. Logical choices include variable message signs (VMS) and highway advisory radio (HAR). Other dissemination media, such as information kiosks and the Internet, may also be used based on feasibility and benefit-cost considerations.

- Traffic Control Center: The traffic control center, if included as part of the loop, will house a computer and several viewing monitors. The information relayed by the roadside computer will be evaluated and verified by qualified personnel. The final decision on the status of traffic and the nature of the information to be disseminated is thus made by a human rather than automatically by a machine.

- Communication Links: Arguably, the most important feature of the system is the communication links between the various components. The communication links make it possible to integrate several technologies and systems together to form the real-time advanced warning and traffic control system. There are several communication links that may be adopted for the real-time work zone system, including radio communication links (Ultra High Frequency, Spread Spectrum, microwave, etc.), cellular links, ISDN links, wireless links, and several others. Appropriate communication links may be chosen for the system depending on the constraints and suitability for each type of link. The key factor to be considered when choosing the communication link is that the chosen link should work reliably at all times. Cost considerations may also affect the decision for a particular communication link.

4.2 System Architecture Issues Specific to I-81

Considering the case of system deployment on the I-81 Corridor in Virginia, special consideration needs to be given to the system architecture based on the future developments that are planned for the Corridor. The system must have an open architecture to ensure its compatibility with any new surveillance or dissemination tools that evolve in the future. It will also facilitate future integration of the system into the Western Virginia Operations Center, which is part of the Smart Travel Business Plan which is an implementation framework for ITS in Virginia (VDOT, 1997a). The Western Virginia Operations Center will be a coalition between the Virginia State Police and the Virginia Department of Transportation. Initially, it will support all traffic signal operations, control, and response to emergency situations for the whole western region of the State. It will also operate as a major communications hub for the entire state, including the I-81 Corridor. When this Center becomes operational, besides being the focal point of traffic operations, emergency response, and communications, it is envisioned to control and coordinate all traffic operations including ITS operations for the western sector of the state. Some of the possible future duties include fleet management, automatic vehicle location (AVL), traveler information, real-time traffic information collection, and ramp metering. The real-time advanced warning and traffic control system is expected to work autonomously and on a point-specific basis, but on the other hand should have the option of being operated by the Western Virginia Operations Center.

Additionally, as part of long range traffic management strategies, VDOT is planning to install permanent variable message signs (VMS) at strategic locations along the street and highway network of the state. Earlier investments in VMS and HAR, in the Northern Virginia and Hampton Roads regions have proven these dissemination devices to be vital communication tools in providing motorists with real-time traffic information. The VMS will be installed in phases at various locations over a period of several years. In the first phase of the project, VMS will be placed at select locations such as Interstate to Interstate connections, Interstate to US Highway connections, state lines, and potential trouble spots along the road network. The VMS will be made National Transportation Communication for ITS Protocols (NTCIP) compliant to allow dual and remote access. The Western Virginia Operations Center is also envisioned to ultimately control all communications to the various VMS that will be located along the entire state road network. Also, to enhance the communications infrastructure along major interstates and highways, VDOT is looking into the idea of resource sharing. As a private-public partnership with the communications industry, VDOT is working to obtain a fiber-optic communications network on interstates and other controlled access highway right-of-way. This will serve the purpose of commercial communication infrastructure development and at the same time provide VDOT and the Virginia State Police with a communications infrastructure for current and future applications of ITS and traffic operations.

In view of all the future developments, such as the development of the Western Virginia Operations Center for centralized control of statewide interstates and highways including the I-81 Corridor, an open architecture is essential for the real-time system at work zones. The idea of resource sharing and potential developments in this area, and the need to comply with NTCIP requirements as they evolve, are other factors that emphasize the need for an open architecture and dictate the openness of the architecture.

4.3 Functional Requirements

Intelligent Transportation Systems (ITS) involve several modern communication systems that provide drivers with real-time information on highway conditions. A variety of products and technologies are currently available and emerging, allowing motorists to receive data and warnings on traffic congestion, incidents, weather and safety. The devices can range from simple equipment, such as the radio or cellular telephone systems with electronic roadside sensors, to more complex devices and systems, such as on-board electronic maps, non-pavement intrusive traffic sensors, satellite location systems, and on-board information systems. The information provided by these systems can be effectively used by drivers to avoid or reduce congestion, incidents, and delays, thereby saving time, fuel, and operating costs.

The development of ITS has spurred the use of advanced technologies in almost every field of transportation. Work zones are no exception: several advanced and innovative technologies have been or are being tested to address traffic safety and control issues at work zones. These include simple innovations such as lightweight changeable message signs (CMS), solar-assisted arrowboards, intrusion alarms, unmanned radars, and complex real-time systems. Recent developments include a combination of technologies that operate as a system to deliver functions such as advanced warning and traffic control in real-time to prevent work zone accidents, minimize delays, and enhance traffic flow. With the multitude of options available in terms of services provided by the use of advanced technologies, there is a need to identify what functions need to be incorporated into such a system so that it will serve its intended purpose and at the same time be cost-effective. Thus, it is essential to develop the system functional requirements before designing the actual system.

A system such as the real-time advanced warning and traffic control system for work zones will be comprised of several components that work together to operate as a single system. Thus, the functional requirements can be viewed as those of the system as a whole, and those of the components forming the system (Figure 10). It is only logical to first define the functional requirements of the system, and then to design system components to fulfill the above requirements.

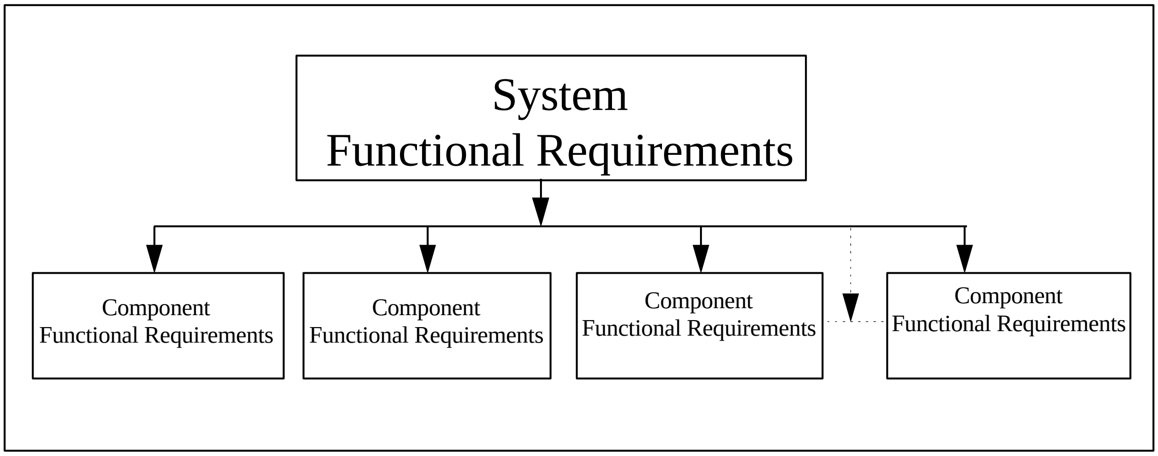

Figure 10. System versus Components Functional Requirements

Before developing the functional requirements of a comprehensive system for work zones, the current work zone issues and problems need to be examined in depth. This will provide guidelines regarding which functions need to be incorporated into the system being developed. The literature review (Chapter 2.0) on work zone accident experiences will help accomplish this task. The real-time work zone system being developed mainly for use on the I-81 Corridor in Virginia, special consideration needs to be given while defining the functional requirements to account for the special geographic and traffic characteristics that are unique to the Corridor. The literature review on the current work zone problems and issues showed that the major problems experienced at work zones were an exceedingly high percentage of rear-end type collisions and fixed object off road type collisions. Analysis of the work zone-related accidents showed that the causes for these collision types were mainly driver inattention, exceeding the safe speed limit within the work zone, and following too close. This trend in work zone accident type and cause was found to be consistent with those reported for several other states including trends experienced on I-81 in Virginia. Table 8 gives a summary of the national scene for work zone accident characteristics.

Table 8. Summary of National Work Zone Accident Characteristics*

WORK ZONE ACCIDENT CHARACTERISTICS	NATIONAL TREND FOR PERCENTAGE OF TOTAL ACCIDENTS
COLLISION TYPE	
Rear-End Collisions	22 % - 57 %
Fixed-Object Off Road	21 % - 53 %
Sideswipe	9 % - 16 %
COLLISION CAUSE	
Driver Inattention	22 % - 48 %
Exceeding Safe Speed	10 % - 13 %
Following Too Close	7 % - 12 %
ACCIDENT LOCATION	
Advance Zone	5 % - 16 %
Taper Zone	8 % - 23 %
Buffer Area	23 % - 54 %

*Data collected is for different studies performed during different years

It includes statistics from several work zone accident studies carried out in different states during different years. Hence, the major work zone accident highlights, such as collision type and collision cause, are presented as a range rather than a specific number. The intention of providing this information is to bring to light the nature and magnitude of the problem experienced at work zones and to show how these problems have influenced the decision for the functional requirements of the real-time advanced warning and traffic control system. Each of the items identified under work zone accident characteristics, such as accident causes, types, and locations has contributed to the development of the functional requirements of the real-time work zone system.

Considering the above work zone safety problems and the four issues identified as concerns to be addressed for the I-81 Corridor, namely work zone safety and control, traffic safety, trucking issues, and intercity traveler needs, the requirements deemed necessary for a real-time advanced warning and traffic control system may be categorized under the following four functions:

1) Surveillance Functions
2) Advanced Warning Functions
3) Advisory Functions
4) Control Functions

The functional requirements developed for the real-time advanced warning and traffic control system were ranked in order of importance to identify which functions are extremely necessary, applicable, and important for the I-81 Corridor in Virginia. Ten transportation officials, including engineers from VDOT and other consulting firms, were contacted and asked to express their opinions on the importance of the functional requirements defined. The officials contacted were asked to rate the defined functional requirements and their sub-functions on a scale of 1-5, with 1 representing least important and 5 representing most important. The scores given to each function and sub-function were summed, and the functions were assigned importance based on the scores they received, the highest being most important. Within each function, the sub-functions were enumerated in a similar manner. It may be noted that the ranking procedure adopted is a preliminary and rough method of rating the functions and sub-functions. Advanced warning functions were voted as most important followed by surveillance, advisory, and control functions.

Figure 11 shows the functional requirements and sub-functions. The sub-functions are arranged in order of importance. Given below is a discussion of the components of each category of functional requirement. The sub-functions for each of the functions are also elaborated.

4.3.1 Advanced Warning Functions

Advanced warning is a means of informing and warning motorists in advance of real-time traffic conditions (including hazardous conditions) prevailing within the work zone, using output devices such as VMS and HAR. Analysis of work zone-related accidents shows that the major cause for collision was driver inattention, and the major type of collision was rear-end. The motorist approaching the work zone is unaware of the traffic conditions prevalent within the work zone and is suddenly confronted by slow-moving or stopped traffic. This poses a hazardous situation where the motorist has very little time to react to the situation and consequently may end up in an incident, adding to the already present congestion. Advanced, real-time, credible warning messages would warn the motorist of traffic conditions ahead, thereby considerably reducing the possibility of an incident

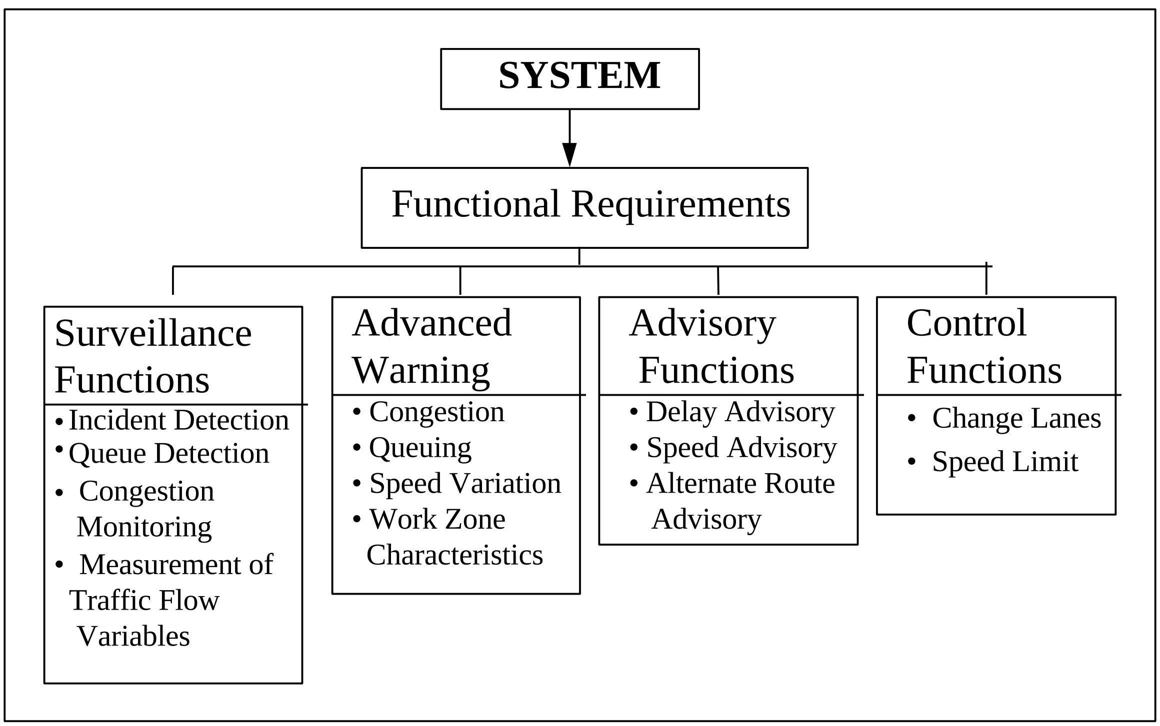

Figure 11. Categories of Functional Requirements and their Components in Order of Importance

leading to congestion and queuing. Thus it is important that the system be capable of providing credible advance warning to motorists, in real-time. The system should be able to warn motorists about the following:

- **Congestion:** Congestion within the work zone poses safety hazards to motorists approaching the work zone and formation of congestion leads to reduction in the speed of traffic. Motorists unaware of this situation may approach the work zone at high speeds and when confronted by slow-moving vehicles, may not be able to prevent a collision. Delays are an inevitable consequence with the occurrence of congestion within the work zone. To help reduce the build-up of congestion and reduce the delays associated with it, delay information must be disseminated to motorists. The information must be given to the motorists in a timely and appropriate manner such that they can alter their travel plans to avoid the congestion. Thus, for safety reasons, the system should be capable of providing warning messages indicating the speed and location of congested flow to prevent accidents and further build-up of congestion, and also provide information regarding the delays associated with it near and within the work zone. This will help in reducing accidents and delays caused due to sudden, unexpected changes in traffic flow experienced near and within the work zones. For efficacy, this warning must be activated automatically at the appropriate time and location.

- **Queuing:** Queuing is a consequence of either extremely congested traffic conditions or an incident. A queue in a work zone can be the most hazardous situation a motorist experiences if he or she is not adequately warned of its presence. Thus, providing advanced warning of the presence of queues is one of the most essential elements of the real-time advanced warning and traffic control system. It is a follow-up function to queue detection. As part of this function, the system should be capable of:
    1. forewarning upstream motorists about the presence of a queue downstream

2. providing this forewarning in an automatic, timely, and appropriate manner, and at an appropriate location, so that the motorists upstream are able to take measures to avoid the hazard
3. real-time operation, with adaptability to change messages/warnings consistent with dynamically changing traffic conditions

The warning of the presence of queues should be done automatically once a queue is detected by the system within the work zone.

- **Speed Variation:** A typical work zone can be divided into five areas/zones, namely the advance area, the taper, the buffer zone, the construction area, and the termination area. Due to the difference in physical characteristics of these areas/zones, the speed of traffic varies in each of the zones. The speeds of traffic may also vary in each zone due to the occurrence of an incident or the formation of congestion and queues. Studies show that the taper and buffer areas are most prone to accidents. This may be due to the fact that in a taper area, motorists are trying to merge due to the presence of a closed lane ahead and there is a reduction in roadway capacity. The system should be capable of monitoring speeds at various locations within and near the work zones (upstream and downstream) and report the changes in speeds or speed variance downstream, within, and upstream of the work zone. This information can be used to warn drivers of what to expect ahead, and in the event of any incident or congestion resulting in the slowing down of traffic and the formation of queues and/or congestion, this can help reduce the possibility of rear-end collisions or added congestion.

- **Work Zone Characteristics:** Additionally, the system should be capable of providing information regarding special characteristics of the work zone, if necessary. For example, if the work zone requires that the roadway geometrics be modified temporarily, this information needs to be clearly conveyed to the motorists to reduce the risk of incidents. Several states have used lighted guiding devices to help motorists comprehend changes in work zone characteristics. This is especially helpful during night-time driving. In the event of an unconventional work zone layout, the system should be capable of highlighting work zone geometrics for night-time driving through work zones.

4.3.2 Surveillance Functions

Surveillance can be defined as monitoring the area under consideration to obtain the status of traffic and detecting any abnormal traffic flow conditions. The system should be capable of performing traffic surveillance and obtaining updates on the status of traffic within and around the work zone. This function is very important and will help in maintaining traffic flow. In the event of an incident/accident or congestion, quick detection via surveillance can help prevent the build-up of long queues and dissipate traffic congestion quickly. Under the surveillance category, it would be desirable that the system have the following capabilities:

- **Incident Detection:** Varying from a stopped vehicle on the shoulder to a serious accident, incidents are the primary cause for congestion and queuing. Incidents cause a reduction in roadway capacity, thereby affecting traffic flow and consequently leading to traffic congestion, reduction in speeds, and queuing. Thus, it would also be highly desirable for the system to have capabilities of incident detection. For minor incidents such as a stopped vehicle on the shoulder, quick detection and immediate implementation of corrective measures would help in eliminating the possible formation of congestion. In the event of major accidents, quick, automatic incident detection would help reduce rescue and clearance times, thus minimizing traffic delays and safety hazards. It would also help render speedier medical service to the people involved in the incident. Thus, from a safety standpoint, incident detection is an important aspect that needs to be incorporated as part of the system to enhance work zone safety and facilitate traffic control.

- **Queue Detection:** The formation of traffic queues within and upstream of work zones is a common phenomenon and poses a very hazardous situation to traffic approaching the work zones. The main cause for queues at work zones may be traced to traffic congestion, incidents, and an increase in demand over available roadway capacity. Once a queue is formed, if corrective steps are not taken immediately, it propagates, rapidly increasing in length and posing a serious hazard to oncoming traffic. Especially on high speed facilities, queue formation can prove extremely dangerous as motorists traveling at high speeds might be unable to react in a timely and appropriate manner when they encounter an unexpected queue. These situations could lead to potential accidents, especially rear-end collisions causing the situation to worsen. Thus, effective and timely warning about queues is essential in enhancing work zone safety. For accomplishing this, the presence of a queue must first be detected. Therefore, a primary functional requirement of a real-time advanced warning and traffic control system must be the ability to detect the presence of a queue. Once the system is capable of detecting the presence of queues, it should also be capable of:

(a) detecting the location of the queue

(b) detecting the length of the queue, and its termination point

(c) detecting the dynamic changes in the characteristics of the queue in real-time, including its propagation, direction of movement, and changes in the location of the end of the queue.

The above information can be effectively used to warn approaching motorists about the hazards ahead, as well as to reduce the speeds of upstream traffic. This would in turn help in reducing congestion and accidents.

- **Congestion Monitoring:** Congestion is one of the most commonly experienced features in and around work zones. Billions of dollars are lost annually due to traffic congestion. There can be several causes for congestion, such as slow moving vehicles, reduced roadway capacity, major and minor accidents, and stopped vehicles. All of these affect the flow of traffic, thereby reducing the speed of traffic or bringing it to a complete halt. The consequences are unwanted delays and motorist frustration. The system should be capable of monitoring the congestion near and within the work zone and thus help reduce the problems associated with traffic congestion. The system should also be able to perform using an algorithm that detects traffic flow variables. Using this algorithm, the system should be able to automatically detect the congestion and display appropriate messages (advisory, warning, or control) on strategically located variable message signs or through other media.

- **Measurement of Traffic Flow Variables:** The working of the entire real-time system for work zones depends on the accurate measurement of traffic flow variables. Variables such as speed, flow, and occupancy will form the basis for many of the algorithms to be used for congestion monitoring, incident detection, and queue detection. More importantly, the variables should be measured in real-time to provide dynamic up-to-date information to motorists. Thus, it is essential that the system be capable of measuring traffic flow variables such as speed, flow, and occupancy in real-time. This would help in monitoring the flow of traffic and assessing the level of service, in addition to facilitating incident detection, congestion monitoring, and queue detection.

4.3.3 Advisory Functions

Advisory functions are functions that provide advisory information regarding traffic conditions and means of reducing congestion, delays and accidents. There is a very fine line distinguishing advisory functions from advanced warning functions. Advisory functions primarily provide the motorist with traffic information to prevent the occurrence of a hazardous situation, whereas advanced warning functions provide motorists with warning messages regarding prevalent hazardous situations within the work zone. In such a situation, the advanced warning functions together with the advisory functions attempt to regulate traffic and manage demand to help overcome the hazardous traffic conditions and return traffic flow to normalcy. The system should thus be capable of providing stand-alone advisory functions, and, in conjunction with advanced warning functions, should include the following:

- **Delay Advisory:** Work zones pose a potential site for the occurrence of traffic delays. The magnitude of these delays may increase considerably during huge construction and maintenance projects. Delays are an unwanted feature and preventive measures are essential to reduce motorist frustration and save valuable dollars. The system should be able to predict delays using special algorithms, and in the event of delay occurrence, it should display appropriate delay advisory messages to inform motorists of the delays to be expected ahead in the work zone. The delay should preferably be expressed in terms of time per vehicle of delay, for example min/vehicle rather than total delay experienced by all vehicles. This makes it easier for the motorist to comprehend the magnitude of the delay and how it will affect him/her.

- **Speed Advisory:** Speeding within work zones is a serious problem faced by officials who work towards enhancing work zone and worker safety. Analysis of work zone safety problems has shown exceeding safe speed to be one of the major causes of work zone accidents. The system should therefore provide advisory signs regarding safe speeds to be maintained near and within the work zones. In the event of congestion or incidents, or if the roadway geometries have been modified, advisory speeds to safely traverse the work zone will greatly improve the movement of traffic and reduce the risk of accidents.

- **Alternate Route Advisory:** Alternate routes work as a means of regulating traffic demand on a highway in the event of excessive congestion, queuing, and delays. In many situations, motorists are wary of leaving the highway and traveling via unfamiliar territory. In some cases, alternate routes may not be available for traffic diversion or may not be open to all kinds of traffic (for example, trucks). In situations where alternate routes are available and can be adopted, the system should be capable of disseminating advisory information regarding alternate route options to help restore traffic conditions back to normalcy as soon as possible. The advisory information should provide detailed, clear, and concise directions on how to traverse the alternate route and should be done via dissemination tools such as HAR and VMS. Information regarding how much longer the alternate route is in comparison to traveling on the highway and approximate time taken to traverse the alternate route will help convince motorists to use the alternate routes. Depending on the nature of travelers (intercity, long distance, commuters, tourists, etc.), a request can be made to local traffic to use the alternate routes, thereby reducing traffic demand on the highway. A survey conducted by a Virginia Tech student on motorist perceptions indicated that people in general are reluctant to leave the highways and use back roads due to lack of proper signing on alternate routes. Good signage of alternate routes can help in encouraging motorists to use these routes, thereby reducing congestion and maintaining smooth traffic flow.

4.3.4 Control Functions

Control functions impose restrictions on motorists in terms of speed and movement. Most departments of transportation (DOTs) are wary of using control signs because they involve several liability issues. Nevertheless, if necessary or in the event of a lane closure or incident within the work zone, the system should be capable of providing some control functions to manage the traffic. These should include:

- **Change Lanes:** There are many different layouts employed for work zones depending on the nature of the work to be done. These may include left/right lane closure, left/right shoulder closure or even median closure. In the event of such a lane closure and change in roadway geometrics within the work zone, requiring motorists to change lanes, the system should be able to provide control signs such as arrowboards, which tell the motorists that they must change lanes. This function, currently being carried out independently, can be incorporated into the real-time system. Some of the respondents of the survey on motorist perception conducted by a Virginia Tech student recommended that there should be a greater number of change of lane signs posted in advance of and near the work zone to help motorists change lanes more quickly, rather than driving until the lane ends and then trying to merge (Martin, 1996). This behavior makes the taper zone and the buffer area just before the construction zone the two most sensitive areas in terms of accident location within the work zone. This recommendation was also made by truckers who find it dangerous and risky when a car tries to merge at the very end of a closed lane.

- **Speed Limit:** As mentioned earlier, one of the major problems experienced in work zones is excessive speeding; a large percentage of accidents within work zones may be attributed to this factor. The system should be capable of capturing driver attention by displaying speed limit signs at appropriate times and locations. If necessary, the system should be capable of changing speed limit signs for different periods of the day, such as night-times when no work is taking place and peak hours of traffic. This will promote speed compliance and enhance motorists' and workers' safety.

Increasing concerns of traffic control and safety at work zones necessitate the use of advanced technologies to address these issues. Use of comprehensive real-time advanced warning and traffic control systems may be the answer to many of these concerns. Before deciding on deploying such a system, there is a need to define the functional requirements of the system. These functional requirements can be broadly classified into four categories, namely, surveillance, advanced warning, advisory, and control functions. Each of these categories can be further broken down into sub-functions, which together will enhance the efficacy of the system. These functional requirements will dictate what technologies need to be incorporated into the system. Besides the functional requirements there is a need to develop certain system requirements that will ensure the adaptation of the system to work zones and their characteristics.

4.4 System Requirements

The functional requirements of the system provide the basis for the type of technology to be employed in assembling the real-time advanced warning and traffic control system. In addition to meeting the above functional requirements, the system must possess several additional features that are deemed necessary for its application to work zones. Figure 12 shows the system requirements for the real-time advanced warning and traffic control system. Each of the system requirements has several options and introduces an additional cost component to the system. Based on preferences and cost constraints each requirement may be considered for the system. Following is a brief description of each of the system requirements:

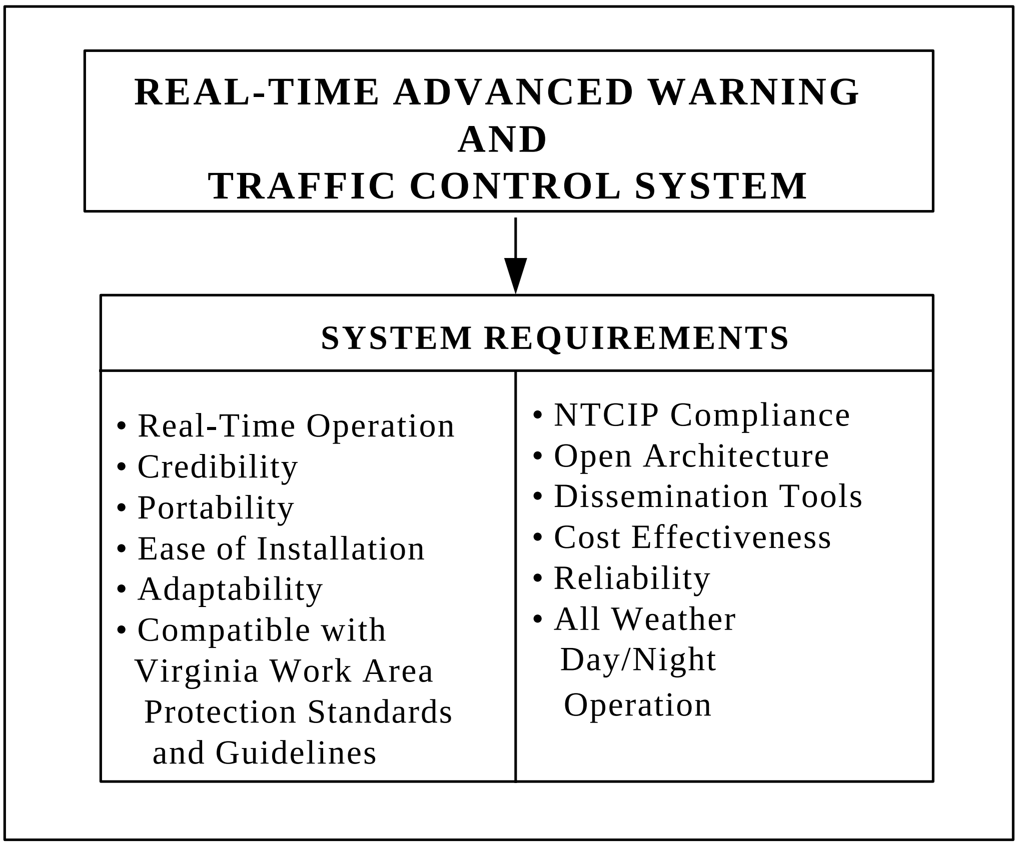

Figure 12. System Requirements for the Real-Time Work Zone System

- **Real-Time Operation**: The fundamental aim of the system is to provide real-time information to motorists, warning them regarding hazardous traffic conditions within the work zone and helping them safely traverse the work zone. In order to accomplish this, the system must operate in “real-time” and be responsive to changing traffic conditions. Technically, “near to real time” operation is required in providing real-time traffic information to motorists. Traffic information may be acquired at thirty-to-sixty second intervals, analyzed, and disseminated as up-to-date or seemingly real-time information to motorists. The real-time operation requirement ensures that the motorist is provided with the latest and current information regarding traffic status within the work zone. The motorist thus finds consistency in the information provided to him and the prevalent traffic conditions. This helps build motorists' trust in the functioning of the system and the information disseminated via the system. For the information to be real-time or near to real-time, the system functions must be satisfied in a dynamic environment. Additionally, the system must also support unmanned operation, as well as monitoring at the site and from a control center (remote site).

- **Credibility:** One of the major causes of accidents at work zones is driver inattention. A probable reason for this could be the loss of credibility of work zone signs and messages as perceived by motorists. Hence, an essential feature of the system should be its ability to effectively capture motorist's attention and promote the credibility of signs and messages. This may be done by attaching time-stamps to each of the displayed messages. In this way, the motorist will know how recent the message is, consequently increasing the credibility of displayed messages and motorist compliance. Also, the messages displayed should be consistent with the existing traffic conditions within the work zone. For example, if a VMS shows a sign saying slow moving traffic 'x' miles ahead, the motorist should not find an open, congestion-free roadway section after traversing those 'x' miles. If the conditions can change in the time that the motorist reaches the point of interest, due notification of the present traffic situation should be given. Thus, when the motorist experiences the traffic conditions he/she was previously warned about, the credibility of the messages and information disseminated increases.

- **Portability:** One of the most desirable features of a real-time system for work zones is "portability." The temporary nature of work zones requires that the system be portable so that it can be moved from one work zone to another with ease and quickness. The different components of the system should be independently portable as well. This is especially useful for components such as VMS and traffic sensors, which, depending on the conditions within the work zone, may have to be moved upstream or further downstream of the work zone. Ideally, the different components should be trailer-mounted to have the desired amount of portability to either move the entire system from one geographic location to another or to move single or multiple components within the work zone itself. If certain equipment requires controlled environmental conditions, such as a computer, it may be housed in a construction trailer that is portable. Trailer-mounted equipment would be ideal and extremely portable but may pose a problem in terms of the space available for trailers to be placed along the roadway. If feasible in terms of cost, for short-term and small work zones where ample space is available, trailer-mounted equipment may be used. Alternatively, for long-term work zones, requiring the hardware to remain in the same position for a long period of time, temporary tripods or stands may be used. For long term work zones lasting more than a week, the system would be considered portable if it requires no more than three days and a crew of seven workers to install.

- **Ease of Installation:** The real-time advanced warning and traffic control system will be used for different kinds of work zones, including short-term and long-term construction and maintenance projects. To encourage its use for all types of work zone projects, the system should be easy and quick to install, and should require minimum man-power. It may not be possible to have the system installation be extremely easy and quick, but an effort must be made to make the system as easy and quick to install as possible.

- **Adaptability:** The changing nature of work zones and the need to deploy the proposed system to different types of work zone layouts require that the system be adaptable to different kinds of work zones at different locations. As mentioned earlier, there are several work zone layouts, including left/right lane and shoulder closures. Each of the work zone types requires a different layout for the system components.

Therefore, the system should be as modular and adaptable as possible to accommodate changes in system component location in order to effectively carry out its functions and maintain smooth flow of traffic within the work zone.

- **Virginia Work Area Protection Standards and Guidelines**: The system must be designed to conform with the appropriate standards and guidelines. In Virginia, the "Virginia Work Area Protection Manual for Street and Highway Construction, Maintenance, and Incident Management Operations (Part VI)" (VDOT, 1996b), has been issued to promote a uniform standard of traffic control associated with special events, incident management, and work area protection along the highways. The components of the system must be compatible with existing VDOT equipment to help reduce system cost.

- **NTCIP Compliance:** The Virginia Department of Transportation requires that all devices (such as VMS) used for the system be NTCIP compliant. The National Transportation Communications for ITS Protocol (NTCIP) provides a flexible and adaptive communications protocol for ITS. It facilitates the interoperability and interchangability of devices, thereby eliminating the need for conversion boxes and reliance on a single vendor for supply of equipment for the system (NTCIP Steering Group, 1996). Thus, NTCIP allows different types of devices to be connected using the same communication medium. The NTCIP Steering Group has defined two communications profiles for traffic control devices, namely CLASS A and CLASS B type profiles. The CLASS A profile is expected to be used for communications between devices and central controllers, while the CLASS B profile is expected to be used for communications between the central controller and various devices. In the context of the real-time advanced warning and traffic control system, the CLASS A profile may be used for communication between devices and between the roadside central computer and a traffic control center, which may be the Western Virginia Operations Center for I-81 in Virginia. The CLASS B profile may be used for communications between the roadside central computer and the traffic sensors, VMS, HAR, and other dissemination devices that may be employed by the system. The NTCIP family of protocols include four profiles, namely CLASS A, B, C, and E. Although, all of these profiles are defined, they require further research and study to be finalized as standard communication protocols. Considering the evolving nature of NTCIP, the real-time advanced warning and traffic control system must be NTCIP compliant to the extent possible, thus enhancing its adoptability by different agencies and in varying circumstances. If any of the equipment to be used does not currently have a standard communications protocol, it should be capable of being upgraded at a later stage to be NTCIP compliant. Currently, standard communications protocols have been developed for variable message signs (VMS), protocols for other equipment, such as sensors, are being developed. NTCIP compatibility will also support open architecture characteristics for the system, which will be another essential requirement.

- **Open Architecture:** The system must have an open architecture to ensure that the system is compatible with any new surveillance or dissemination tools that evolve in the future. It will also facilitate future integration of the system into the Western Virginia Operations Center, which is part of the Smart Travel Business Plan for ITS in Virginia (VDOT, 1997). When this Center becomes operational, it will be the focal point of traffic operations and control for the whole western region of the State, and will include control of the real-time systems at work zones. An open architecture is thus essential to integrate the operation of the real-time advanced warning and traffic control system as part of the Center. The idea of resource sharing and potential developments in this area, and the need to comply with NTCIP requirements as they evolve, will also dictate the openness of the architecture.

- **Dissemination Tools:** The dissemination tools to be used by the system should be such that the information is available to practically all traffic. Potential candidates include variable message signs (VMS) and the highway advisory radio (HAR). Use of other dissemination tools, such as the Internet and information kiosks, may also be used depending on the magnitude of the project and the benefit cost analysis of having such a medium of information dissemination. These are not real-time information dissemination tools, but they may be used for long-term construction projects to increase awareness of work zone activity and inform the public about work schedules. These information dissemination tactics may help manage traffic by encouraging people to avoid the work zones, thereby reducing demand along the affected roadway section. When deciding on the dissemination devices to be used local restrictions should be taken into account. For example, to use portable HAR as a medium of dissemination, easy availability of a radio frequency should be ensured.

- **Cost Effectiveness:** The system should be cost effective. Operation and maintenance costs should be analyzed and budgeted in future funding cycles. The system should also be cost effective in terms of installation; minimum manpower should be required to set up the system. The use of solar-powered arrowboards and VMS and components with low maintenance requirements are means of reducing the operation and maintenance costs of the system.

- **Reliability:** System reliability is an important requirement that needs to be fulfilled. The technologies employed in the building of the system should be reliable in carrying out the operations intended without any failure or false alarms. Besides the individual components, the entire system resulting from the integration of the different components should work reliably and without any malfunction. The system basically consists of two major components, the hardware and the software. The software should be extremely reliable, work effectively at all times, and should not fail without adequate warning. In the event that the software fails, the system should default to displaying signs that warn motorists and operators that the system is not working. For example, if the software fails, the VMS may display messages such as “SIGN TEST” rather than leaving it blank, where motorists would believe that there is no problem to be expected ahead. The hardware components should be reliable to the extent that they should be capable of withstanding all known and expected problems. For example, if the equipment will be used in areas subjected to high wind speeds, the hardware components should work reliably under such conditions without losing its alignment or working in a faulty manner. Thus, in the interest of motorist safety, it is extremely essential that the system be reliable to work with, ensuring minimum or no system failures and false alarms.

- **All-Weather Day/Night Operation:** The system should be rugged and capable of working reliably in all weather conditions and during day or night conditions without breaking down or working at reduced efficiency. This requirement ensures that the system can be used for day or night-time construction activities and may even be used continuously over a period of time involving several days and nights. The ruggedness of the system ensures its safe and efficient operation during varying weather conditions. Thus, the system should employ equipment that has been tested for all-weather and day/night operation. The system should be capable of withstanding two tests to ensure its all-weather day/night operation. First, it should be capable of working continuously over a period of time without failure, and second, it should work efficiently even after it has been left unused for a particular period of time.

Based on the developed system requirements, functional requirements, and the considerations for a suitable system architecture, an appropriate real-time advanced warning and traffic control system may be designed. The designed system should fulfill all system and functional requirements and conform to all architectural requirements for its application to the I-81 Corridor. The real-time work zone system, once designed and developed, needs to be evaluated for its effectiveness in meeting all system and functional requirements. The following chapter identifies evaluation criteria and measures of effectiveness (MOEs) that may be used for the evaluation of the system. Additionally, issues related to the evaluation of the system are identified and examined as part of the next chapter.