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Guidelines for Development of Smart Apps for Assessing, Coding, and Marking Highway Structures in Emergency Situations

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SUMMARY

This technical manual provides a guideline for developing mobile devices-based smart applications for PDA responders (PDARs) for their use in emergency scenes for assessing, coding, and marking transportation structures. The primary intent of this manual is to facilitate communication between structural engineers, respondents, inspectors, and the IT professionals who will develop and manage the application and associated data. The smart application automates the manual and paper-based assessing, coding, and marking procedures, which are described in detail in *NCHRP Research Report 833: Assessing, Coding, and Marking of Highway Structures in Emergency Situations, Volume 2: Assessment Process Manual* and *Volume 3: Coding and Marking Guidelines*. This manual includes guidelines for developing interfaces, basic functions, and server or cloud-side services to support the smart functions.

1 INTRODUCTION

This manual presents a guideline for developing a smart device-based application (Smart App) software system for automating manual and paper-based Preliminary Damage Assessment (PDA) for highway structures in emergency situations. The primary intent of this manual is to facilitate communication between structural engineers, respondents, inspectors, and the Information Technology (IT) professionals who will develop and manage the app and associated data. In other words, it helps the structural engineers with communicating the needs of the app and how it may interface with their current procedures. It helps IT staff understand the overall process and what features are needed in the app.

A full PDA process includes the steps of assessing, coding, and marking of transportation structures following an emergency event. The objective of PDA is to quickly inspect and assess highway structures that were determined at risk from the precedent Fast Reconnaissance (FR) stage. The assessment step is focused on helping a PDA responder (PDAR) determine the overall condition of the structure. The coding step entails documenting specific damages in a simplified fashion and providing an overall rating for the structure. Each highway structure should be evaluated in its entirety as well as at the level of system elements. PDA should only result in a structure being coded and marked as INSPECTED or UNSAFE. The marking stage consists of physically marking the structure with a placard as well as digitally marking the structure in a geospatial information system (GIS) database.

Complete details regarding the PDA objectives and consequences are seen elsewhere in *NCHRP Research Report 833, Volume 3: Coding and Marking Guidelines*.

This Smart App runs on a smart device, which relies on its back-end server for data storing, retrieving, processing, information retrieval or relaying, and providing aggregated results. Therefore, the resulting Smart App system is a client-server software system. A generic name for the developed software system is used in this manual – Smart Applications for Transportation Structures Assessing, Coding, and Marking (SmartTS-ACM). The basic functions of this system include:

1. Primary function: automating the assessing, coding, and marking (ACM) functions to enhance the efficiency of field-based ACM procedures.

2. Auxiliary function: providing GIS-based analytics and data sharing functions that visualize aggregated ACM products to the DOTs' management and other emergency response engineers.

1.1 Background and Motivation

Field inspection can generate a large amount of data including digital images, video streams, text-based narratives, voice recordings, and other logged data. Therefore, computer-aided data collection, archival, or even data processing in the field become desirable and enables rapid data synching and coordination between field crews and office analysts. Mobile computing devices, which feature mobile communication, computing and interactive (touch-based) screens, and data processing software, have been actively used in many engineering practice (e.g., various brands of mobile laptops, rugged tablets, and smart devices).

Feedback from the emergency responders at the state's DOTs from a recent questionnaire (See the NCHRP 14-29 Interim Report) indicates that the majority of respondents (92%) store their structural assessment data in a digital format that is accessible during an emergency situation. This implies that digital database and data sharing technologies that are based on classical computer servers or workstations are being treated as a standard IT infrastructure and routinely being adopted. The questionnaire results also revealed that for structural condition assessment, compared with different low- or high-tech technologies, smartphones and tablets are given higher priority in emergency events. *This implies that the community is keen to using smart mobile technologies for rapid emergency response.* These questionnaire results provide motive for the development of this manual which provides the descriptions of the basic functions of the Smart App software system.

1.2 Technology Maturity

The latest smart devices, including smart tablets and smartphones, integrate a variety of advanced hardware and software systems for sophisticated multi-functionality. Today's mobile devices tightly integrate multi-core central processing units (CPUs), graphical computing units (GPUs), high-resolution cameras, flexible communication, wireless networks (e.g., 3G/4G cellular network, WiFi including WiFi Direct, Bluetooth, and near-field communication), interactive interface through sensitive touch screens, geographical positioning, and embedded

gyroscopic and acceleration sensors. With the basic smart functions including high-quality imaging, geo-tagging, and communication, smart devices tend to replace many conventional single-function mobile devices, such as phones, cameras, and GPSs.

It is also noted that to date the use of smartphones or tablets have truly become ubiquitous. In the meantime, numerous smart apps with different functionalities have been developed and are being used by the public. From this point of view, today's smart devices and smart apps are both commercially and socially mature. For the latter (social maturity or 'user maturity'), evidence from the questionnaire results of this project reveal that the emergence response engineers at the state's DOTs fully embrace the use of smart devices (and the applications) in practice.

1.3 Related Smart Apps for Structural Condition Assessment

Similar mobile applications that focus on structural condition assessment exist to date. The most relevant one is the Rapid Observation of Vulnerability and Estimation of Risk (ROVER), which is a mobile-device and server-based software system for both pre- and post-earthquake building safety screening (FEMA 2011). ROVER automates two paper-based seismic safety-screening procedures that are outlined in (1) FEMA P-154, Rapid Visual Screening (RVS) of Buildings for Potential Seismic Hazards, and (2) ATC-20, Post-earthquake Safety Evaluation of Buildings.

While automating the paper-based procedure, the developers of ROVER state that it has the following advantages that would be not available if the traditional paper-based procedures are solely used. These major advantages include: (1) print-ready digital forms that emulate original paper worksheets; (2) unlimited captioned or watermarked digital photos with automatic geolocation; (3) integrated data management that aggregates digital photos, sketches, and entry data in one database; (4) integrated high-resolution hazard mapping data; (5) easy export to Google Earth; and (6) optional integration with ShakeCast and Hazus-MH. Figure 1-1 shows the workflow how ROVER is used during an earthquake cycle. In the meantime, a user community has been established around this app as indicated on the website of ROVER (FEMA 2015a).

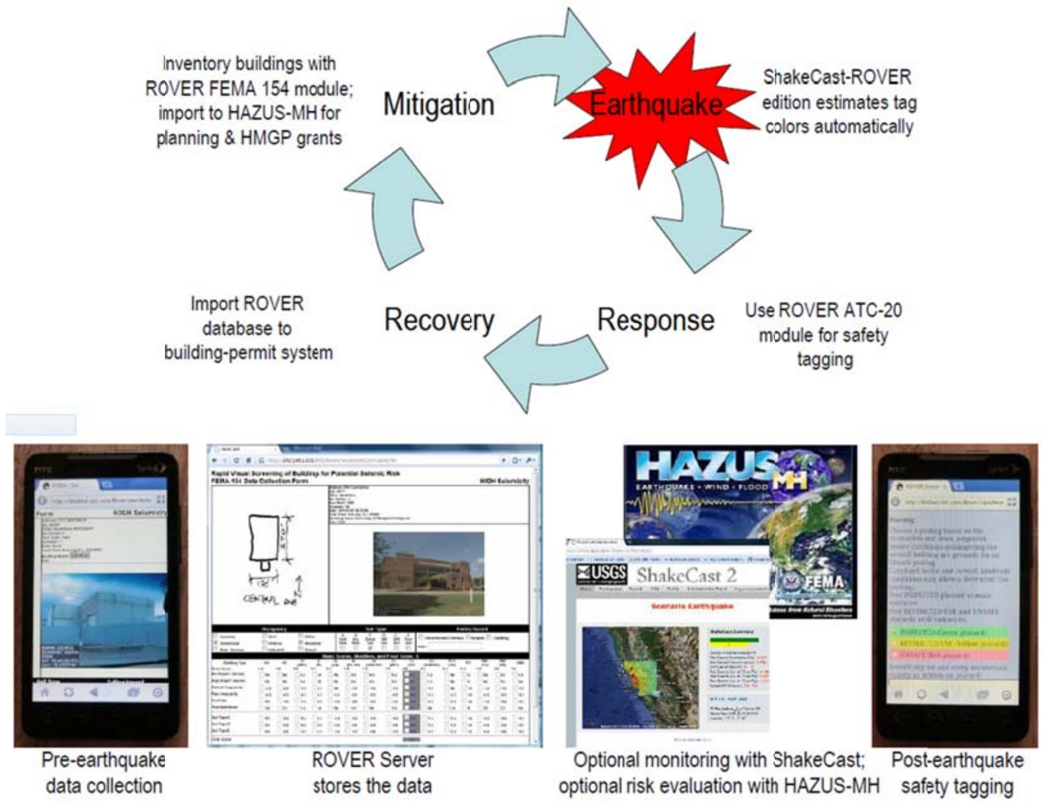


Figure 1-1: ROVER workflow during an earthquake cycle (FEMA 2015a).

Since many of the ACM procedures developed in this project refer to similar ATC-20 procedures, the developers of SmartTS-ACM may refer to the development of ROVER as a starting point. However, two important differences of SmartTS-ACM from ROVER are highlighted.

1. In SmartTS-ACM, the types of emergency events are multiple. For most DOTs, they face multi-hazard challenges for their transportation inventories; whereas ROVER currently focuses on earthquakes only.
2. In SmartTS-ACM, the types of transportation structures are multiple. ROVER focuses solely on building structures. For most DOTs, their inventories of transportation structures include bridges, culverts, tunnels, and others.

These differences imply that first, for the DOT-based developers of SmartTS-ACM, preliminary customization and high-level planning prior to the software development (i.e., determination of types of emergencies and structures) should be conducted. Second, the fact that SmartTS-ACM considers multiple types of emergencies and structures poses a challenge for developers towards developing a unified user-interface system.

1.4 Organization and Scope

The objective of this guideline is to provide basic characteristics of the Smart App (the front-end interface), the architecture of the software system, the server design, and the PDA's ACM procedures that need to be followed and adapted for the software design. In the following sections, this guideline includes the following contents:

- Section 2: Field Operation Workflow and Data Generation Workflows
- Section 3: Data Structures: Variables, Data, and Interoperability
- Section 4: Dependencies and Worst-Case Scenario
- Section 5: System Architecture and Essential Functions
- Section 6: Mobile Front-End Interface Design
- Section 7: Server Design and Services Design
- Section 8: Crowdsourcing And Smarter Functions
- Section 9: Conclusions

1.4.1 Scope of Development

The front-end application of the software system starts with considering the select types of emergencies and structures by a DOT. The emergency type and the structure type, once obtained, serve as the entry variables that initiate and guide the PDA responders (PDARs) to take actions and enter relevant field data through the Smart App's front-end. The front-end application should be portable to major brands of mobile devices (including Windows, Android, and iOS devices). The back-end server provides data receiving, storing, sharing, analyzing, aggregating, and security services, which can be implemented in workstation servers, virtual servers, or in a cloud infrastructure. Therefore, the development of SmartTS-ACM essentially includes (1) mobile front-end interface design; and (2) server back-end service development.

1.4.2 Disclaimers

1.4.2.1 For Target Users

The target users of this app are professional PDARs who work in the field during the aftermath of an emergency event that impacts regional transportation structures. It is essential that PDARs should be trained during emergency preparation activities based on the developed

PDA procedures from this project. Therefore, the developers of this guideline assume that the users of a realized SmartTS-ACM application have been trained properly and henceforth take no responsibility of any misuse of the application.

1.4.2.2 For Target Audience (Software Engineers)

The target audience of this technical manual is software (architecture and programming) engineers affiliated with the state DOTs. The guidelines suggested herein are at a high level interfacing between the PDARs and the software engineers. As such, the manual focuses on defining data workflows, software system architecture, and required major functions that are outlined in the ACM procedures. The suggested system components, programming languages and protocols, data and service types, are further subject to technical detailing using formal software design and modeling languages (e.g., Unified Modeling Language for software design; Entity Relation Diagram for relational database design).

It is important to note that it is the responsibility of the software engineers, the PDARs, and their supervisors at a state DOT for customizing the basic functions of the SmartTS-ACM. With this basic understanding, the software engineers should be capable of customizing the suggested software architecture and functions in this manual that agree with the experience, training, tools, and other preparation routines in their home DOTs.

2 FIELD OPERATION WORKFLOW AND DATA GENERATION WORKFLOWS

The purpose of defining the primary operation workflow and the associated data workflow is to prepare a systematic ‘big picture’ for the software engineers who need to understand the basic procedures of performing assessing, coding and marking in the field that are conducted by the PDARs who are not software engineers. The operational and data workflows are illustrated based on the ACM procedures developed for PDARs. A detailed description of these procedures is seen in *NCHRP Research Report 833, Volume 3: Coding and Marking Guidelines*, Section 3.4. In addition, the general emergency response levels are found and described in *Volume 2: Assessment Process Manual*, Section 5.2. Figure 2-1 depicts the operational action and the data generation workflows for a team-based ACM process.

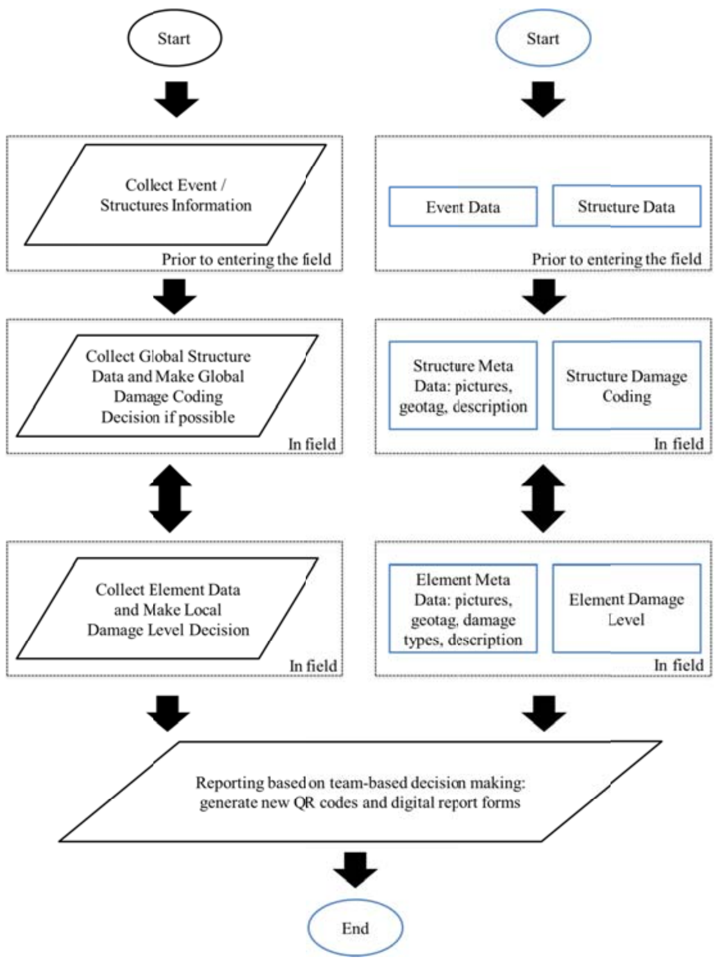


Figure 2-1: Field operational (left) and data generation (right) workflows for a PDA team-based ACM procedure.

3 DATA STRUCTURES: VARIABLES, DATA, AND INTEROPERABILITY

Field assessment followed by coding and marking, regardless of paper-based or Smart App-based, involves collecting and logging data to the designed data entries. For designing and programming towards realizing the SmartTS-ACM software, this implies that internally a set of global variables will be defined in the programs that await user's input values or assigning values from existing databases. Many of these variables are hierarchically or causally related. Therefore a data structure is needed to describe the relations of the basic variables that are involved in PDA procedures.

3.1 Data Structures

Based on the operational and data workflows in Figure 2-1, data structures for developing the Smart App are proposed in this section. The data structure design is critical prior to developing the software system (both the mobile front-ends and the back-end services). The following data structures are suggested.

For the front-end, the developed interfaces should guide the users to provide data associated with the variables pertinent to emergency event, observation, and condition that are necessary for making the final coding and marking decision for the structure. For the back-end services, the variables form the basis for constructing the databases (i.e., tuples and attributes in a SQL database; or keys in a NoSQL database). Once filled with ACM data (i.e. values assigned to attributes or keys in a database), the resulting databases further provide the sources for situation sharing through querying and further the basis for making higher-level decision in the case of emergency events.

The following hierarchical charts provide a sample design of the variables and their sample values (Figure 3-1 – Figure 3-3). In these charts, the variables are circled by ellipses, sample values, and their acquisition methods (under ideal situations) are noted in brackets. Detailed database design is necessary further but subject to the software engineer's choice on database types. This manual does not have preference to using either traditional SQL databases or modern NoSQL databases. However, a formal database design (e.g. entity-relationship modeling for a SQL database or a JSON-based modeling for a NoSQL database) may be entailed towards ultimately implementing the proposed data structures into an appropriate database.

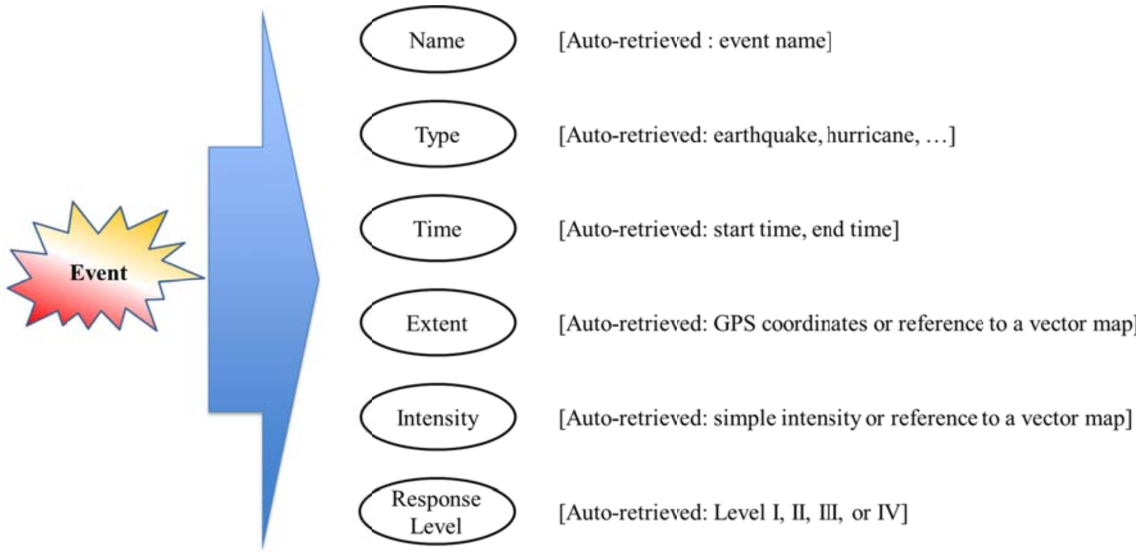


Figure 3-1: The data structure with Event as the parent attribute and six variables to define the event.

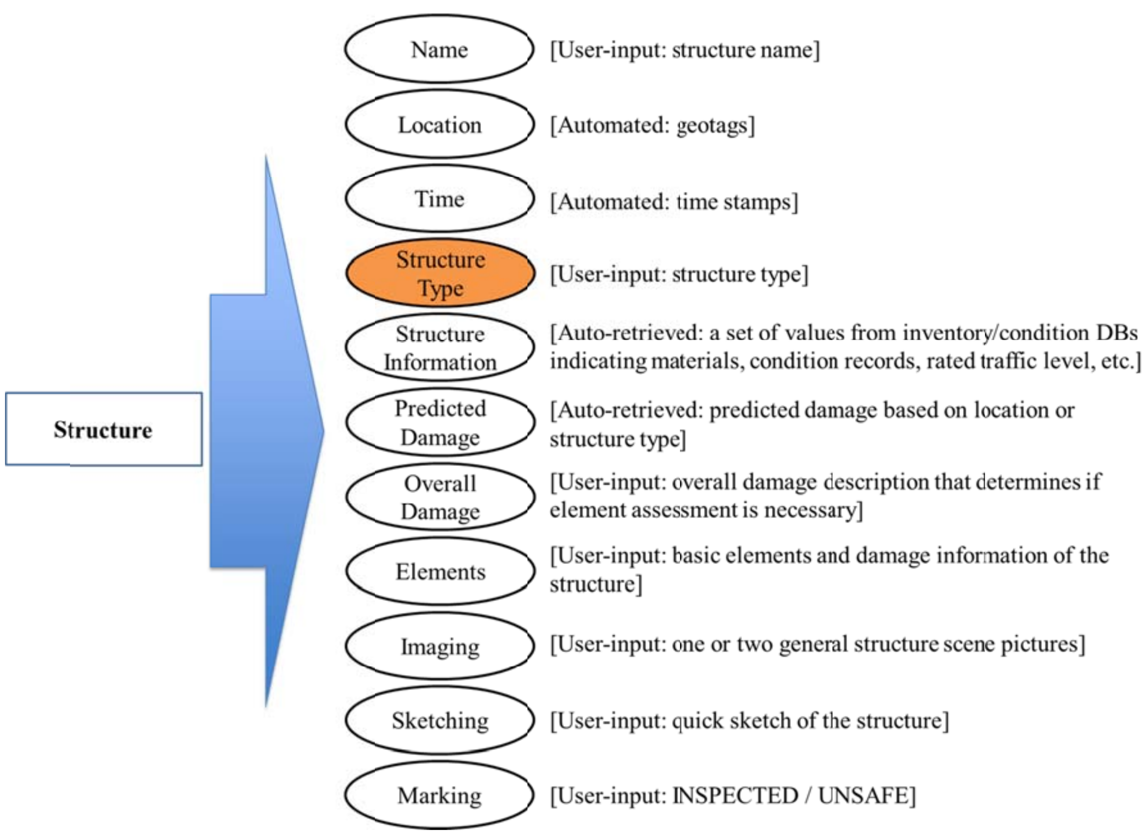


Figure 3-2: The data structure with Structure as the parent attribute and 11 primary variables describing the structure and its elements. The "Elements" variable will lead to a sub-tree variable set (Figure 3-3). In addition, the "Type" variable is considered as the primary variable that is set at the outset of the ACM procedure.

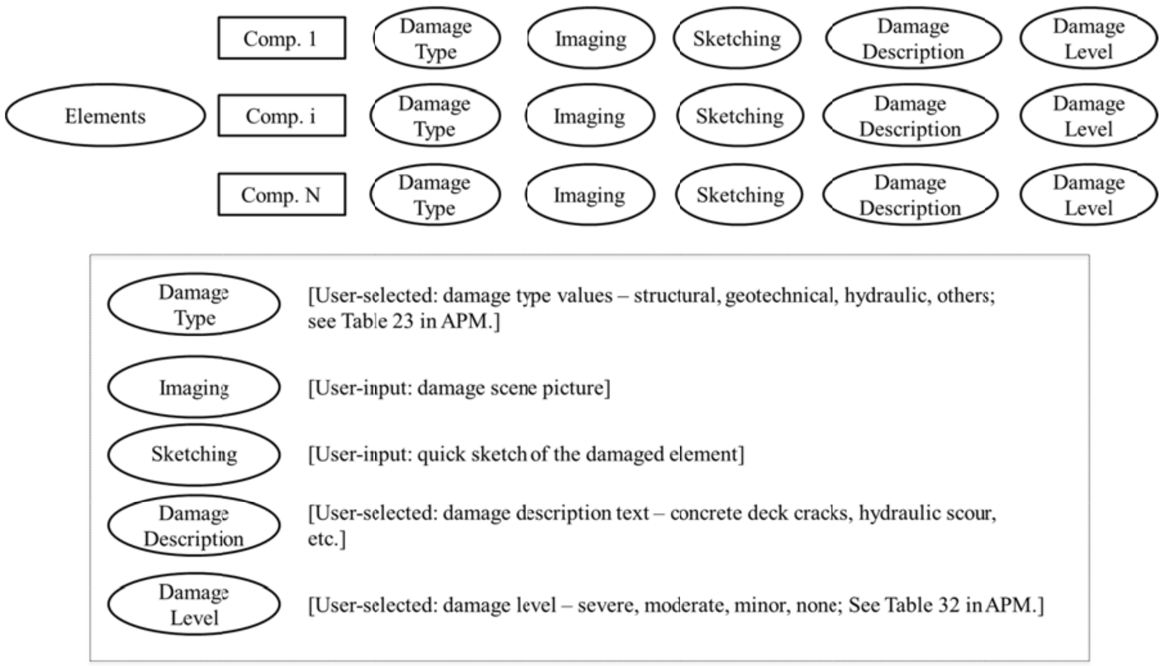


Figure 3-3: The data structure with each select Elements as the sub-parent parameter; for each element, a set of parameters are used to describe the damage level of the element: damage type, damage description, evidence picture, and the damage level.

Collection of data or retrieving data for assigning values to the above variables will be realized through the client-side (the mobile front-end) interfaces that are connected to and aided by the services in the remote server. It is obvious that ideally for the event information (when existing databases and near real-time post-event intensity mapping are available), the basic event and hazard information can be automatically retrieved from the server for the field reference. For example, USGS provides ShakeMaps and other metadata of an earthquake event in a few minutes, which can be pushed to users or agencies who subscribe this service. It is emphasized again that if these information is not available, the PDARs may still proceed and perform ACMs based on their training, experience, and team collaboration.

3.2 Data Interoperability

Potentially the above data structures including the involved variables and their multi-media values (numeric, text, sketches, and images) can be represented using standard XML-based and machine-readable documents. In addition, part of the above variables, especially those related to structural properties, elements and systems, can use coded number or names as used national or state-developed inventory standards, such as the national bridge inventory (NBI).

One NCHRP report (Ziering and Harrison 2007) extends the standard XML schema and developed TransXML for data sharing and exchange in the transportation sectors. This standard can be further extended to adapt to the assessing, coding and marking procedures and to the above data structures. Different from the database design and modeling languages used by the software engineers, this possibility is solely suggested herein if data interoperability is of critical concern for transportation officials when facing inter-state, regional, or national level emergency situations.

4 DEPENDENCIES AND WORST-CASE SCENARIO

4.1 Software and Application Dependencies

The proposed SmartTS-ACM system relies on a set of dependencies for its use in the practice. The basic dependencies are tabulated in order to use the SmartTS-ACM in the field. Developers of SmartTS-ACM will use these dependencies to test and verify the system prior to pushing the Smart App into practice. These dependencies include: (1) Existing databases; (2) Hazard or loss estimation data products; (3) Mobile and server hardware; and (4) Networking and communication. For each item, the level of dependency is suggested.

Table 4-1: Practical use dependencies for the SmartTS-ACM.

<table>
<tr><th>Category</th><th colspan="2">Sample Item</th><th>Level of Dependency</th></tr>
<tr><td rowspan="3">Existing Databases</td><td colspan="2">Transportation structures inventory databases (e.g., National Bridge Inventory [NBI])</td><td>Strongly recommended</td></tr>
<tr><td colspan="2">Transportation structures condition database</td><td>Strongly recommended</td></tr>
<tr><td colspan="2">Location data of transportation structures</td><td>Required</td></tr>
<tr><td>Hazard or Loss Estimation Data Products</td><td colspan="2">MH-HAZUS-based loss estimation mapping products;
ShakeCast or NOAA’s Hurricane/Storm Surge Hazard</td><td>Recommended</td></tr>
<tr><td rowspan="9">Mobile and Server Hardware</td><td rowspan="6">Smart phones/tablets</td><td>Imaging</td><td>Required</td></tr>
<tr><td>Computing</td><td>Required</td></tr>
<tr><td>3G/4G communication</td><td>Required unless loss of access due to damage</td></tr>
<tr><td>GPS</td><td>Required</td></tr>
<tr><td>Voice recognition</td><td>Optional</td></tr>
<tr><td>Internal storage (besides SIM cards)</td><td>Recommended</td></tr>
<tr><td colspan="2">2nd Digital cameras</td><td>Optional</td></tr>
<tr><td colspan="2">2nd GPS device</td><td>Recommended</td></tr>
<tr><td colspan="2">Remote servers or cloud infrastructure</td><td>Required unless loss of access due to damage</td></tr>
<tr><td rowspan="3">Networking</td><td colspan="2">3G/4G networking</td><td>Required unless loss of cellular infrastructure due to damage</td></tr>
<tr><td colspan="2">WiFi hotspot</td><td>Optional</td></tr>
<tr><td colspan="2">Satellite phones or other communication devices</td><td>Strongly recommended (in case of loss of 3G/4G cellular network)</td></tr>
</table>

Given Table 4-1 and the levels of dependencies, the baseline infrastructure for developing and using the SmartTS-ACM is proposed, which should be versatile enough to address different

scenarios of digital connection, from the *in-situ* network connection, delayed network connection, to the conventional connections relying on digital data cables or storage media. This baseline infrastructure includes:

1. Modern smartphone or tablets with basic imaging, text/voice/gesture interfacing, general computing, GPS capabilities, and sufficient local storage that can work with and without digital connection with the remote server;
2. A remote server (or cloud infrastructure) that can receive and store field data from the smart devices accommodating to the aforementioned different scenarios of digital connections.

4.2 Worst-Case Scenario

Based on the above development dependencies and baseline infrastructure, the worst-case scenario for using the potential Smart App is further described, for which the software engineers need to consider during the development cycle of this app. This worst-case scenario basically features the situation wherein no digital network connection (neither WiFi Hot Spot nor cellular networks) is available to the PDARs in the field. This scenario implies that smart devices are unable to connect to the Internet *in-situ* hence to the back-end servers in the real time.

The software design should consider this scenario and warrant that PDARs can continue to use their smart devices alone without connecting to the server and then perform ACM in the field. This means that a PDAR can perform ACM based on his/her training, experience, and basic aids such as GPS positioning. Once the field data and individual PDAR's coding/marking data are saved offline in local storages of the mobile devices, these data can be uploaded to the remote server when digital networks (such as WiFi hotspots or cellular services) become available at a delayed time and in a different place.

The ultimate fail-safe plan is to manually upload data to the servers by using digital data cables (USB cables) or digital storage media (e.g. USB flash drives). Regardless of the delayed d network-based or manual data uploading, the servers will provide unified data aggregation and analytics services to save and process the field data. Therefore, high-level decision-making by the emergency response officials can still be conducted at the DOT's headquarters.

5 SYSTEM ARCHITECTURE AND ESSENTIAL FUNCTIONS

5.1 System Architecture and ACM Functions

The system architecture and the primary ACM related functions of the SmartTS-ACM system is suggested in Figure 5-1.

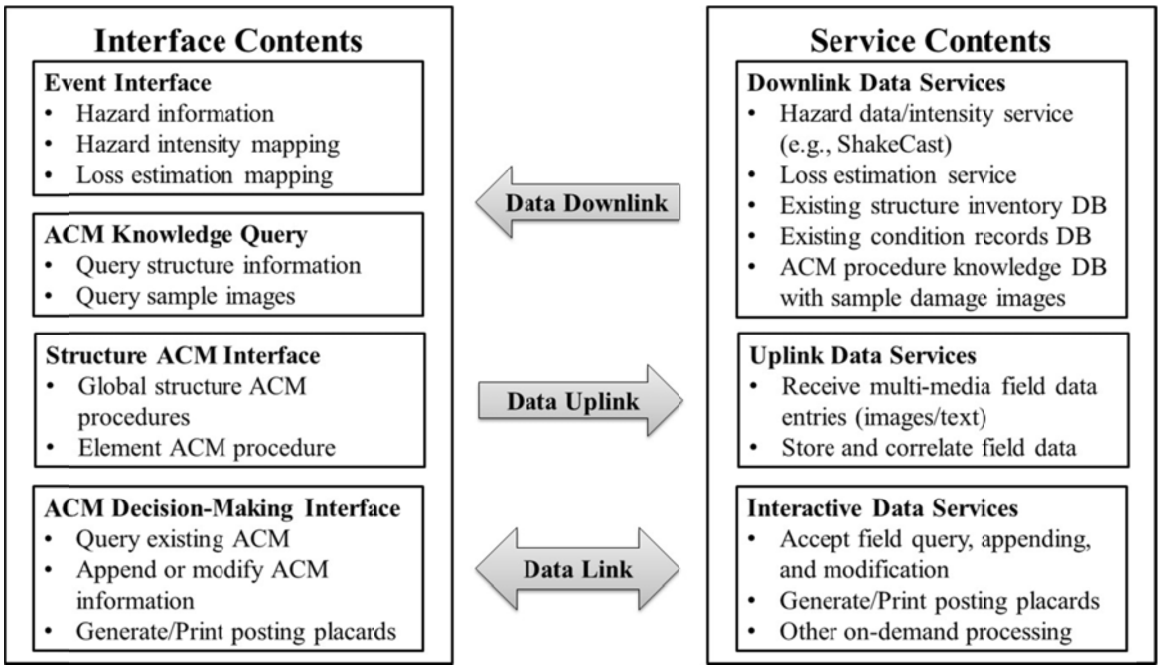


Figure 5-1: Suggested system ACM function architecture design and basic functions grouped as modules of the SmartTS-ACM system.

In Figure 5-1, two software subsystems are shown including the client-side interface functions and the server-side services (collectively function modules). The proposed architecture design in Figure 5-1 suggests the essential functions and services, which are grouped as different modules. For practical implementation, it is up to the software engineers to decide how to group these functions in different modules.

5.2 User Registration and Logging Function

Atop the ACM function modules as shown in Figure 5-1, the Smart App automatically and immediately incurs a user ID logging interface when one opens the App. Two types of user IDs may be designed depending on the server design. The server may provide registration service for registering and logging the user information for the following two categories of users.

1. Registered USERs – PDARs and management engineers who conduct field assessment, coding and marking, or making decisions based on their higher authority.
2. Training USERs – trainees who are under PDA training and the APP training. The registration service will allow the users in this category to access data specially developed for the training purpose.

6 MOBILE FRONT-END INTERFACE DESIGN

6.1 Main Entry Interface

After logging in, the Smart App provides a unified interface for initializing the main functions of the app. The primary interface is suggested as shown in Figure 6-1, which provides the primary entry menu to four major function interfaces.

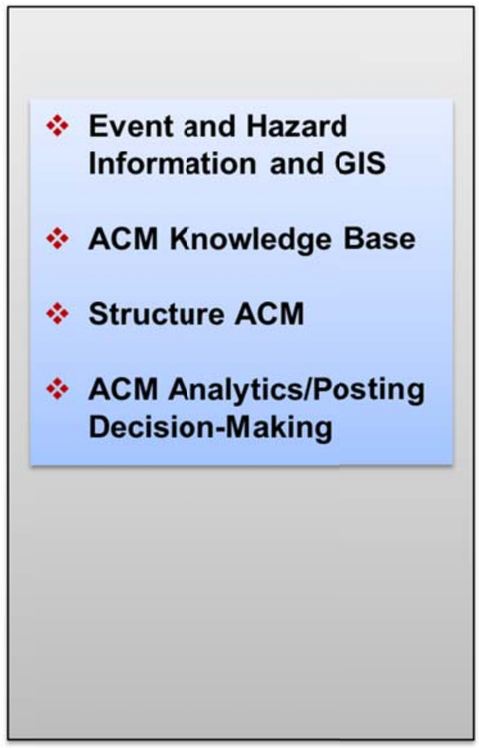


Figure 6-1: Entry menu to the three main function interfaces.

The four menu items are the entry points to the corresponding function interfaces. As will be detailed in the following, the most critical function interfaces for realizing PDA functions are (1) Structure ACM Interface and (2) ACM Analytics/Posting Decision-making Interface, whereas the Event and Hazard Information Interface and the ACM Knowledge Base Interface can greatly assist the two PDA function interfaces.

In the following, these guidelines introduce the basic features of the Event and Hazard Information Interface and the ACM Knowledge Base Interface; then focus on the latter two interfaces and suggest basic design layouts.

6.2 Event and Hazard Information Interface

The Event and Hazard Information Interface primarily retrieves the **event** (the hazard), **hazard-based data**, and **emergency response** information, and provides an interactive mobile environment that assists the PDAR's on-demand and real-time decision-making. The basic characteristics of this interface include:

1. The event information includes the basic extent, time, single scalar-valued intensity measures, and other geospatial mapping products that are relevant to the event. The mapping products should be overlaid with general mapping products showing routes, terrain, or even real-time traffic/blockage information. These mapping products will provide decision-making aids for route planning for the PDARs before entering into emergency zones.
2. The hazard-based data are ideally interactive mapping products – especially those that are obtained immediately after the event related to hazard intensity or even estimated damage severity. These products will greatly assist the route planning and guide the PDARs emphasis on transportation structures in the priority areas. For earthquake events, these include ShakeMap or ShakeCast mapping data; for hurricane or storm surge, these may include estimated peak gust wind speed mapping or flooding inundation mapping; and for tornados, this may be the tornado track or radar mapping data. Planning-based hazard damage estimation products, such as those generated by Hazus-MH (FEMA 2015b), may be shown as well. Due to the planning and the risk-based nature of these products, these estimated losses and mapping products may provide important reference values.
3. The emergency response information should include the determined event response level, which is ideally determined during the FR stage (*NCHRP Research Report 833, Volume 2*, Chapter 5.2). This event response level can be further linked to the procedure in the ACM Knowledge Base, which is convenient for PDARs in the field.

Difficulties for developing this Event and Hazard Information Interface may include visualization and display of mapping products that are further backed up by the server-side services. Considering today's major GIS-based platforms, such as Google Maps and ESRI ArcGIS, which often provide Application Program Interfaces (APIs) for both mobile client and

server developments, these difficulties are recognized but can be overcome by using these commercial APIs subject to significant customization efforts.

6.3 ACM Knowledge Base

ACM Knowledge Base Interface serves the PDARs who are in the field and are in the process of assessing a structure of interest. The basic design methodology for this interface is suggested as follows:

1. This interface should be activated anytime for querying particular ACM procedures or sample images of particular damage patterns using gesture-based shortcuts.
2. For keywords and key procedures in other function interfaces, hyperlinks should be provided such that the PDARs can enter readily into the corresponding knowledge base at request.
3. A search interface should be provided within the Knowledge Base that assures searching ready for key words or phrases.

For the contents of the Knowledge Base, the following contents are suggested:

1. The technical ACM manuals in PDF or HTML formats.
2. The major tables, charts, and procedures for ACM that are all indexed and searchable.
3. The sample pictures of structural, geotechnical, and hydraulic damage for each category of structures under each type of emergency.
4. Other relevant manuals and guidelines, which may include:
    a. FHWA's *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, Report No. FHWAPD-96-001 (FHWA 1995). Key tables in this guide include those coding schemes for bridge materials and structural elements, which are useful for field evaluation including assessing, coding and marking. Such a table is seen in Table 6-1.
    b. FHWA's *Bridge Inspector's Reference Manual* (Ryan et al. 2012).
    c. AASHTO's *Manual for Bridge Evaluation* and *Manual for Bridge Element Inspection* (AASHTO 2011; AASHTO 2015).

Table 6-1: NBI coding for bridge material (field 43A) and design (field 43B) (FHWA 2015).

NBIS Code 43A – Material	
Code	**Description**
1	Concrete
2	Concrete continuous
3	Steel
4	Steel continuous
5	Prestressed concrete*
6	Prestressed concrete continuous*
7	Wood or timber
8	Masonry
9	Aluminum, wrought iron, or cast iron
0	Other

* Post-tensioned concrete should be coded as prestressed concrete.

NBIS Code 43B – Design	
Code	**Description**
1	Slab
2	Stringer/multi-beam or girder
3	Girder and floor beam system
4	Tee beam
5	Box beam or girders – multiple
6	Box beam or girders – single or spread
7	Frame (except frame culverts)
8	Orthotropic
9	Truss – deck
10	Truss – thru
11	Arch – deck
12	Arch – thru
13	Suspension
14	Stayed girder
15	Movable – lift
16	Movable – bascule
17	Movable – swing
18	Tunnel
19	Culvert (includes frame culverts)
20	Mixed types*
21	Segmental box girder
22	Channel beam
00	Other

6.4 Structure ACM Interface

Structure ACM Interface has two hierarchical levels – the global structure ACM and the element-level ACM. In some situations a structure's general damage patterns (e.g., collapse, partial collapse, or significant superstructure/substructure failure that is visible to naked eyes from distance) enable it to be easily determined as 'UNSAFE', without entering to the 2nd level of element-level ACM. Herein, details in suggested interface design are given for the global level ACM; and the element-level ACM is given in Section 6.5.

As shown in Figure 5-1, the structure ACM interface acts to automate the PDA procedures, except for the final posting decision (which is a team-based decision). Among the basic variables as shown in Figure 3-2, it is suggested that the variable 'Structure Type' be treated as the primary variable provided by the PDAR at the first place. The 'Location' variable can be automatically obtained from the smart device's geo-positioning function. Based on 'Structure

Type' and 'Location', the meta-variable 'Structure Information', such as materials of structures, service years, existing condition records, and certified traffic levels (for bridges), may be automatically retrieved from the databases of Structure Inventory, Structure Condition Records, and the hazard-based loss estimation. It is noted herein that values to these variables from the back-end databases may use codes as previously shown in Table 6-1. Therefore, the aforementioned knowledge base may assist the PDARs to recognize those codes.

The primary ACM interface is suggested in the following (Figure 6-2). These interfaces are designed in a way that when a PDAR is selecting each menu item, a direct input window or another lower-level interface will appear that awaits the PDAR's input or auto-fills with values that are retrieved from local time/GPS functions or the back-end services.

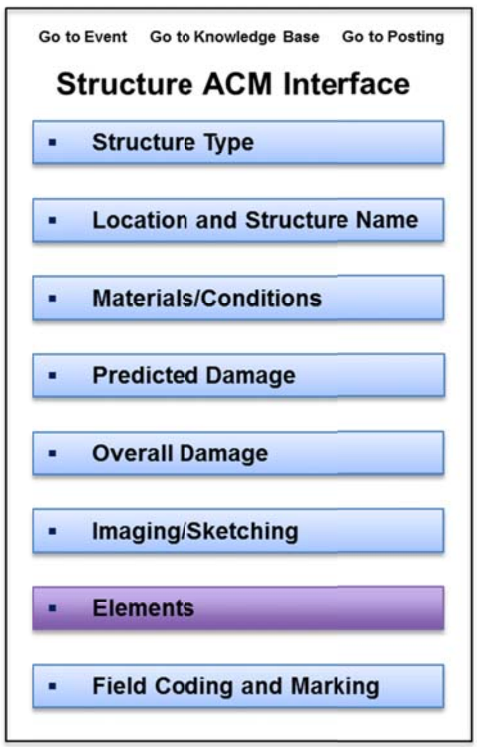


Figure 6-2: Suggested structure ACM main interface with menu items directing to lower-level interfaces.

6.4.1 Structure Type, Location, and Structure Name

Figure 6-3 illustrates suggested interface design for Structure Type, Location, and Structure Name. It shows that once the Structure Type is provided, the Smart App can locate possible hyperlinks that point to possible damage patterns of this type of structure and under the

previously known event type. These existing damage patterns in the Knowledge Base are of great help to the field PDARs.

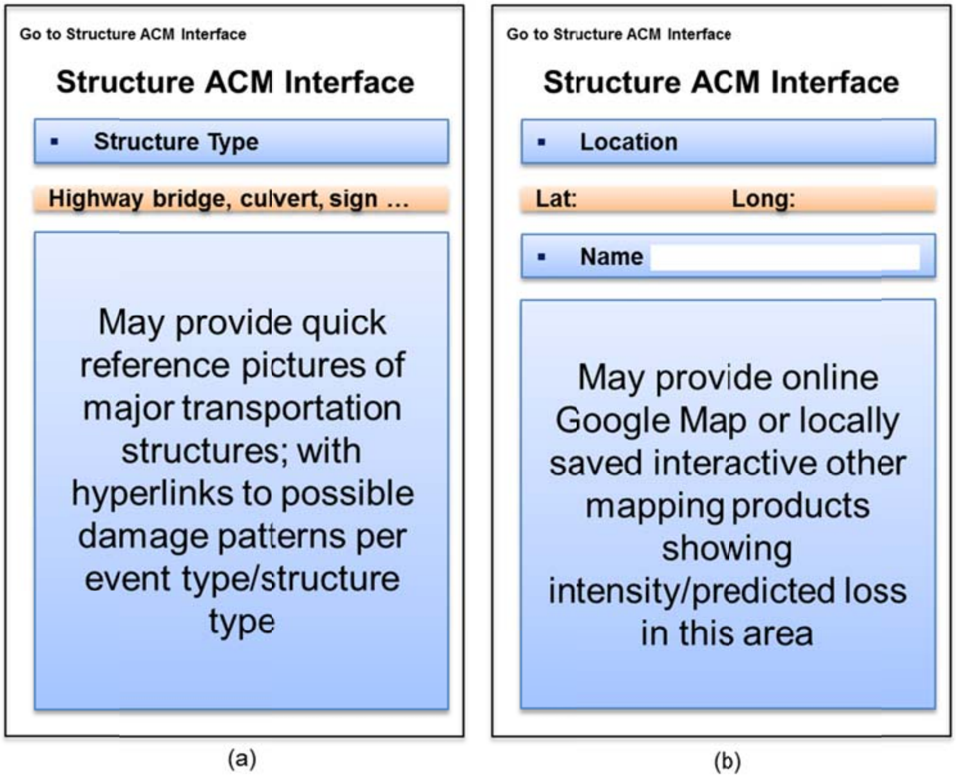


Figure 6-3: Suggested interface design for (a) Structure Type, and (b) Location and Structure Name.

It is noted that geo-tagging and time-stamping are considered automatic functions that run in the background in the smart device. The Smart App calls these functions whenever necessary. For any input event (imaging, narrative, and reporting), a geo-tagging and a time stamp will be added to the data as part of the metadata. With multiple time-stamping from many data entries, a time clustering maybe conducted that collectively shows the ACM activities for a PDAR during the time period.

With multiple geo-tagging, automatic clustering of geolocations (e.g., clustering images that are for the same structure hence enabling unambiguous annotation in GIS layers) should be provided. In the meantime, this auto-clustered geotag may differ slightly from the auto-retrieved structure location from the database that is set during pre-event planning; a threshold-based treatment may be used to indicate such difference is tolerable for the same structure. Although not shown in Figure 6-3(b), the interface may provide a linear reference feature for positioning

the structure and the ACM activity, such as milepost, milemarker, etc. If the PDAR selects to input these linear features, the system can convert them to latitude-longitude locations when the field data is uploaded to the back-end server. It is noted that this optional function would be valuable in an extreme case when even GPS positioning is not available due to malfunction of the mobile devices or the GPS satellites.

With the Location (automatically set) and the name input by the PDAR, an interactive map may be provided under the 'Location/Name' interface. This gives the PDAR the geospatial sense of the structure relative to the extent of structure. If possible, the emergency intensity or even estimated damage in this area (or for this type of structure) can be shown as another layer of the mapping window as well.

6.4.2 Structure Information, Predicted Damage, and Overall Damage Description

Figure 6-4 provides basic interface design for Structure Information, Predicted Damage, and Overall Damage Description. The Structure Information is a meta-variable with many associated variables that can be automatically obtained from back-end databases, whereas the Overall Damage Description awaits the PDAR input based on his/her comprehensive decision on the global conversation.

Under Structure Information, a set of values from the databases are provided for the structural materials and configuration, their conditions in records, the structure service year, and the average daily traffic level if applicable. For professional PDARs (such as structural engineers), this information provides insightful reference for the field observation and decision making.

Predicted Damage is only applicable when planning-based damage estimation is available, such as those based on Hazus-MH modeling. The previous Event/Hazard Information Interface gives a regional mapping-based result. This particular entry retrieves the damage estimation for the current type of structure at this location.

The Overall Damage Description provides the primary entry wherein the PDAR inputs brief description of the observed conditions of the structure (including damage types, damage levels, damage locations, and suggested posting of UNSAFE or INSPECTED). The definitions of damage levels are found in the *NCHRP Research Report 833, Volume 2: Assessment Process Manual*, Table 6-2.

It is noted that this entry also provides a decision-making point regarding whether element-level assessment would be necessary. If it is, a 'Go to Element Assessing' entry is provided that leads to the element-level assessment phase. In the meantime, the PDAR can go back to this entry after the element-level assessment and add more descriptive phrases about the element damage under this entry.

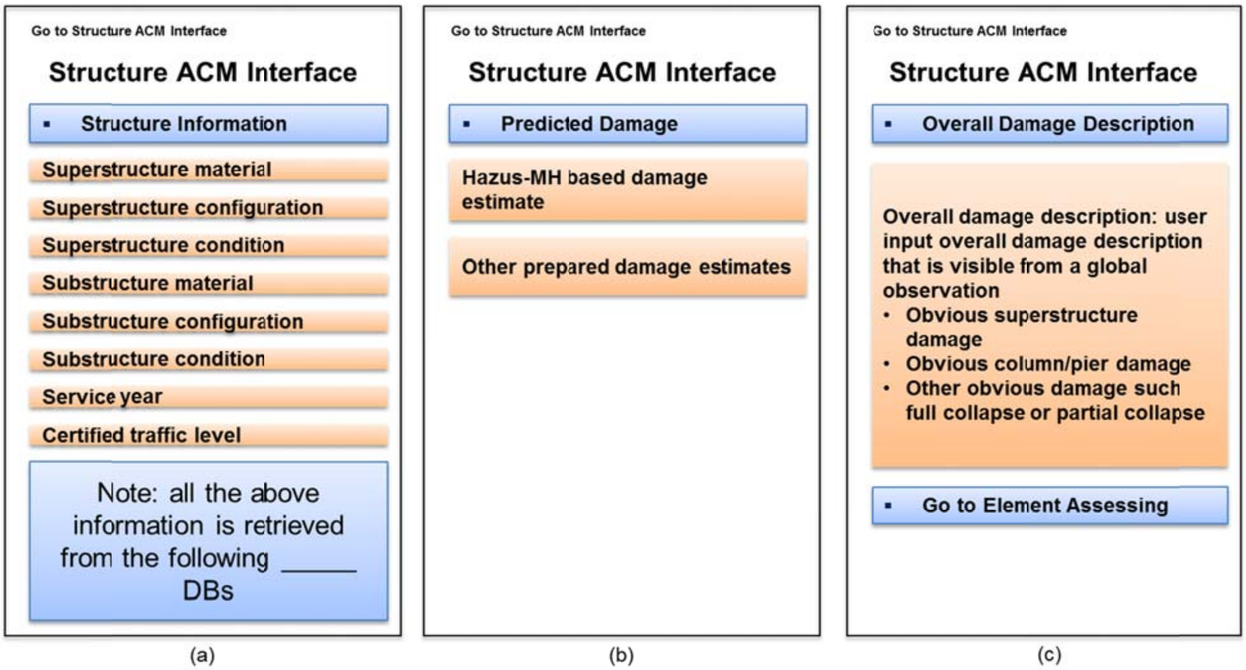


Figure 6-4: Structure ACM interface for (a) Structure Information, (b) Predicted Damage, and (c) Overall Damage Description.

6.4.3 Imaging, Annotation, and Sketching

Modern smartphones are equipped with various high definition cameras and gesture-rich interfacing to general users. This leads to one of the major advantages of using smart devices – the PDAR can augment the paper-based ACM procedures by automatically linking photo pictures and sketches to the observed conditions (that can be only expressed in terms of written description in paper-based procedures).

Figure 6-5 provides suggested interfaces for imaging and sketching. For imaging, which can be realized through calling the smart device's camera API, users can capture static photo pictures or video at any appropriate time and location. However, this convenience, if different kinds of smart devices are considered, yields a technical challenge in treating images from different users and different cameras, which will have different resolutions and different sizes. The imaging

function of the Smart App may be developed to consider a standardized down-sampling process. The images to be uploaded to the server should be of the same size (e.g., 480x720) that warrants in most cases the necessary resolution for defining damage. More advanced computational photography may be utilized (such software-based autofocus, auto-sharpening, or histogram-based intensity adjusting for illumination effects).

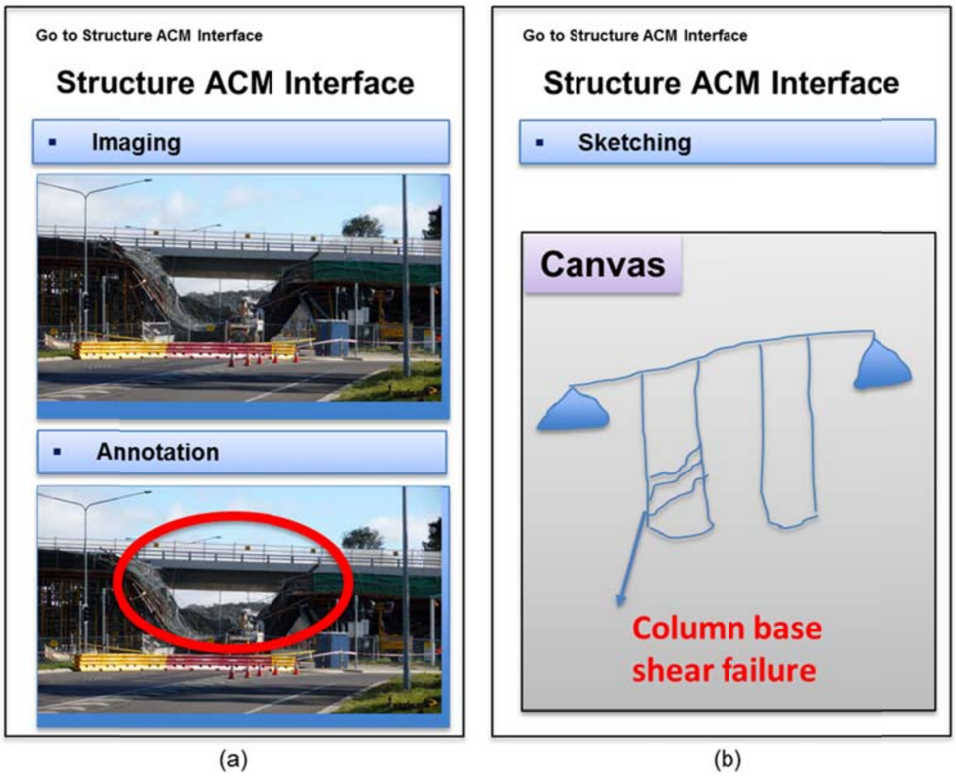


Figure 6-5: Structure ACM interfaces for (a) Imaging/Annotation and (b) Sketching.

When an image is captured, annotation function may be provided that offers the PDAR a straightforward opportunity for adding contextual information to the image, such as location, type, or severity of damage based on gesture analytics (e.g., red circle indicates a severe partial collapse damage; at element level, red lines indicates a severe cracking damage).

Sketching function is of great interest to PDARs and is feasible for smart devices. The sketches with highlights may provide more direct and insightful damage information than pictures can have. Figure 6-5(b) shows a sample sketching, wherein a PDAR draws and annotates with important structural damage description and possibly causal explanation.

The resulting annotated images or sketches in Figure 6-5, both geotagged, can be saved as images and sent to the remote server.

6.4.4 Coding and Marking

Coding and marking in the field is a decision-making process subject to the PDAR's personal observation, experience, and knowledge. Therefore, subjective uncertainty exists. The app design should consider this nature and provide ACM interfaces for a single PDAR as well as interfaces for a decision-making step wherein the PDAR team members make final justification and ACM decisions.

Figure 6-6 provides the coding and marking interface for one PDAR. The PDAR first selects his/her final judgment for the structure, either 'INSPECTED' or 'UNSAFE'. At this point, a hyperlink may be provided that links to the interpretation of 'INSPECTED' and 'UNSAFE' in the Knowledge Base. After the decision is made, a placard is generated with the sample image shown in Figure 6-6(b). It is particularly noted that a QR code is generated for which the information embedded in the QR code can be customized that may include the PDAR's name, date of assessment, the event information, the structure information that is previously shown to the PDAR, and the marking result (INSPECTED or UNSAFE).

It is noted that a final decision to code and mark a structure should be through team-based discussion. Upon the consensus, the final coding and marking may be posted (the posting). This is why a separate and integrated ACM Analytics and Posting Interface is designed later (Section 6.6).

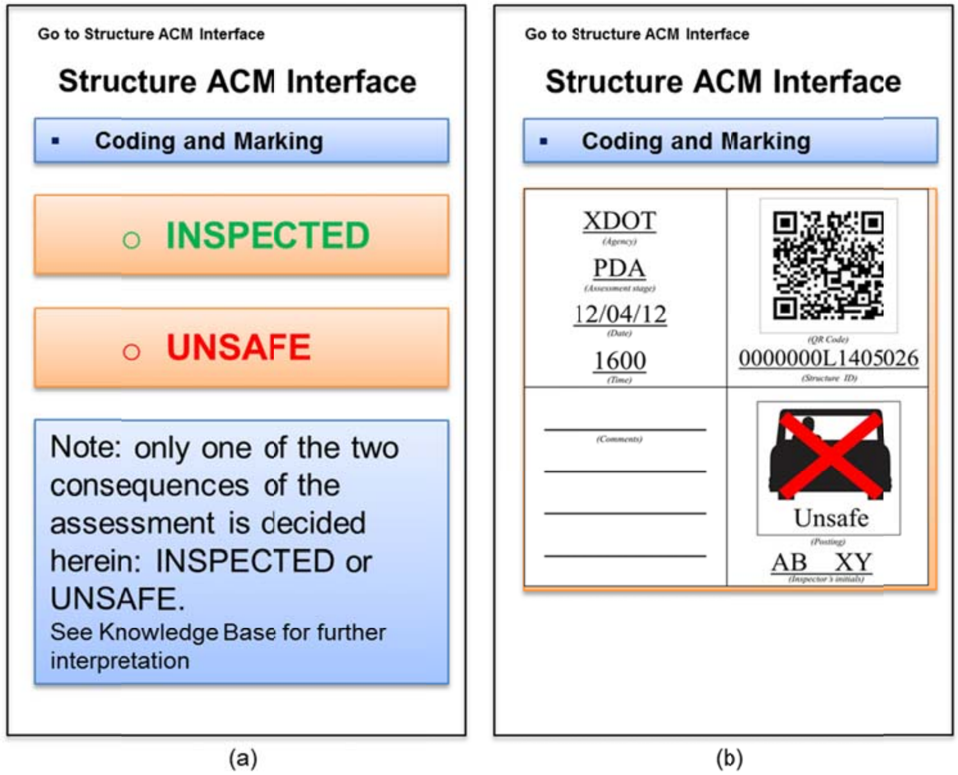
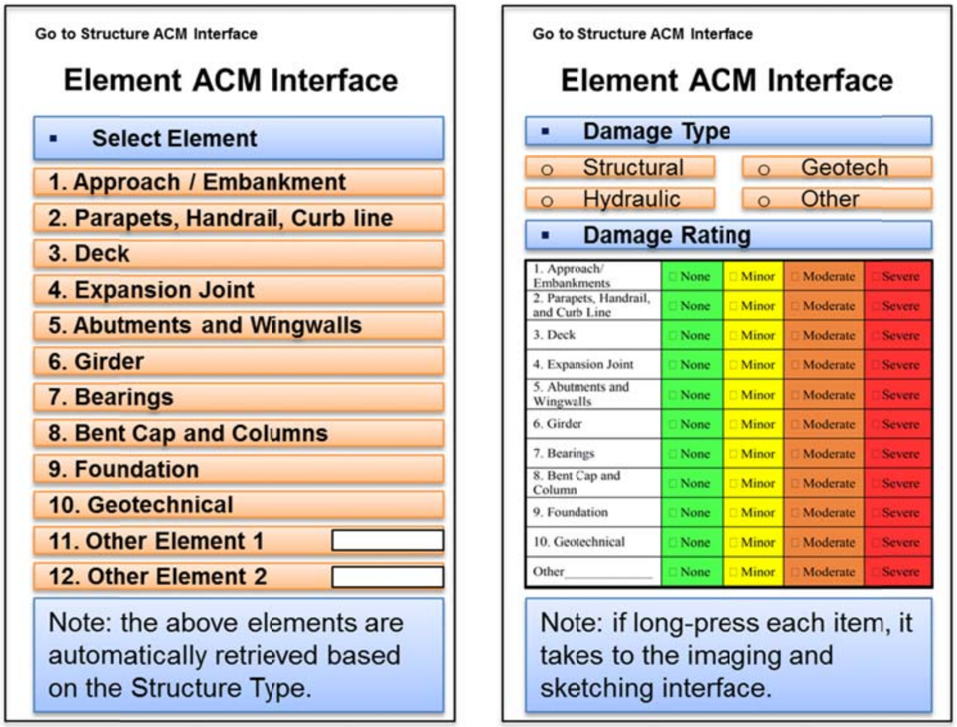


Figure 6-6: Structure ACM interfaces for coding and marking: (a) Marking Decision; and (b) Coded Placard.

6.5 Element ACM

Element-level ACM is necessary when structures show no obvious patterns or signs of major damage that is not visible from a distance; or if there is any doubt regarding the integrity of the structure or regarding the safety of the traveling public. In these cases, a PDAR needs to inspect the structure at the element level. For element-level ACM, the primary variable 'Structure Type' is critical in designing this interface, since different types of structures have different element subsystems.

Figure 6-7 lists the typical elements of a highway bridge. Based on the structure type, different lists of structure elements will be automatically displayed. The PDAR selects the elements that are determined to be assessed in the field. If there are elements that are not listed by the application, the PDAR may manually add more.



(a) (b)

Figure 6-7: Element-level assessment interface: (a) Selecting Element; and (b) Element-level Damage Rating that may be further linked to imaging/sketching interface for any element.

With the elements selected in Figure 6-7(a), a damage rating interface is shown in Figure 6-7(b). Under this interface, Damage Type is first checked appropriately for each element; then the damage level for that element is selected. Prior to going to any other element, the Damage Type should be cleared and a new Damage Type value is selected for the element. Each element is then associated with its specific Damage Type and one appropriate Damage Level value is chosen (e.g., 'none', 'minor', 'moderate' and 'severe') (see Figure 3-3 for the data structure of the variables designed for each element).

Prior to making decision on the Damage Level of any element, imaging, annotation and sketching is useful for describing critical element damage. It is suggested that a long-press gesture may be designed that is activated when one presses an element item in Figure 6-7(b). The imaging, annotation, and sketching interface may be designed as shown in Figure 6-5.

6.6 ACM Analytics and Posting Decision Making

The ACM Analytics and Posting Interface is designed to provide both a team-based data sharing and final coding and marking decision-making interface. Figure 6-8(a) shows a sample illustration of the aggregated results of ACMs from different PDARs for multiple structures.

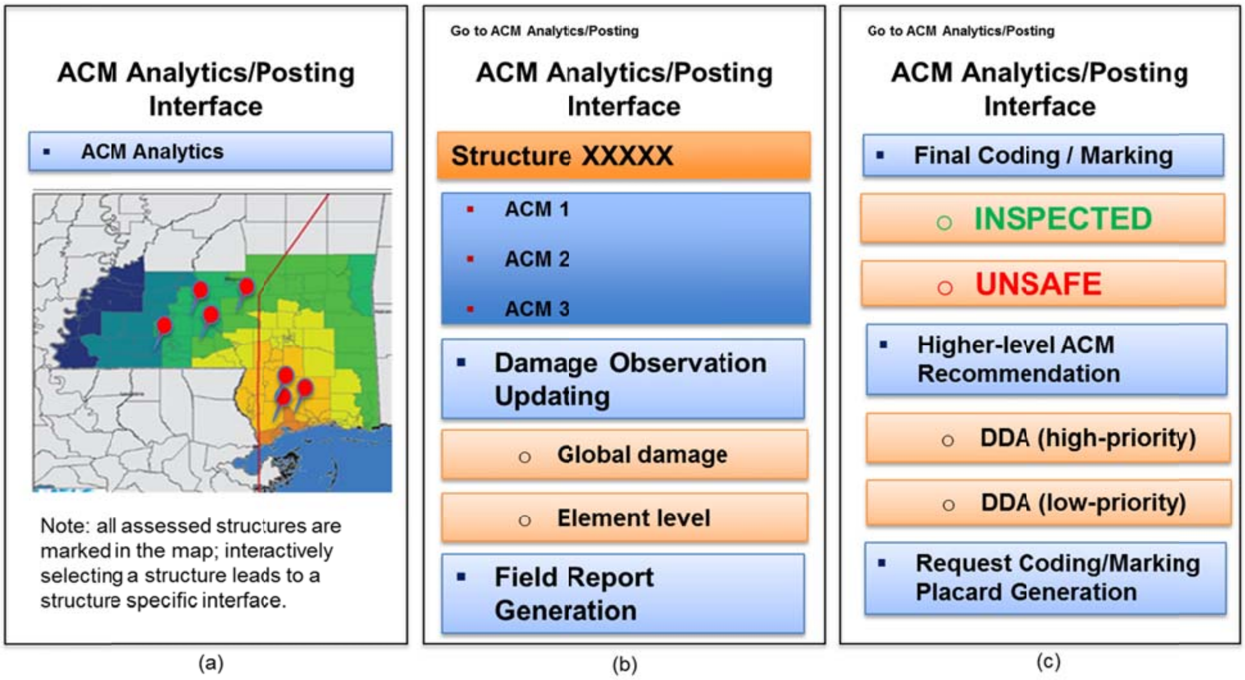


Figure 6-8: ACM Analytics and Posting: (a) aggregated ACM for different structures in an emergency event zone; (b) through QR reading, one select structure with different ACM results, and damage data for the global structure or the elements can be amended (modifying existing data or adding more observation data); and (c) a consensus for the final coding and marking.

First of all, the team members can retrieve any member's logged data, images, damage description and damage levels, and the coding and marking decision. One easy way is through selecting a structure from Figure 6-8(a) interactively; then a structure specific interface can be shown in Figure 6-8(b), wherein all PDAR's ACM results are shown, for example, ACM 1, 2, and ACM3. Selecting any of these ACM results will lead to the individual ACM details.

It is specially noted here that sharing is feasible even without external digital data communication links (e.g. local WiFi or cellular networks for connecting to the remote servers). Based on the available Peer-to-Peer (P2P) communication technologies, available P2P communication in today's smart devices include WiFi-Direct and Bluetooth for connecting devices to devices. With WiFi-Direct or Bluetooth, PDARs can exchange ACM information for

the same structure. This data sharing feature may be enabled automatically when two or multiple PDARs are within the range of WiFi-Direct or Bluetooth at the location of a transportation structure.

This interface primarily serves as assisting the team discussion that may incur necessary editing, updating, or appending the damage assessment for the structure. Upon consensus, the agreed damage description and damage levels for the structure and its elements can be finalized. A final Coding/Marking is then made given the consensus (Figure 6-8[c]).

This interface also can act as a mobile-end information sharing and decision making for the emergency management engineers and officials who practice their duties at the DOT's emergency response offices and make decisions on the DOT's emergency response efforts as a whole. For this purpose, functions for this interface can be considerably enhanced based on practical needs. One option is to consider a mobile- and workstation-compatible (even cluster-based visualization system) design for the ACM analytics.

At this point, the final Damage and Element Damage Levels, and Coding and Marking are saved in the remote server. In the meantime, under the interface of Figure 6-8(b), a final report generation function may be activated. This calls for the service of report generation in the back-end and generates a professional PDA report. Figure 6-9 shows such report for the case of bridges.

Preliminary Damage Assessment (PDA) Form – Bridges

Inspector 1 Name/ID: ______	Structure ID: ______		**PDA Outcome:**
Inspector 2 Name/ID: ______	Highway: ______		☐ INSPECTED (Green)
Agency: ______	Milepost: ______		☐ UNSAFE (Red)
Date and time: ______	Route Carried on: ______		
Latitude/Longitude: ______	Route Carried under: ______		
Structure material: ☐ Steel	☐ Concrete	☐ Other ______	

Damage Summary:	**Traffic Level:**	Links to the narrative notes and pictures
☐ 1 – None (0%)	☐ No traffic at all	
☐ 2 – Slight (0-1%)	☐ Traffic on all lanes	
☐ 3 – Light (1-10%)	☐ Traffic on some lanes	
☐ 4 – Moderate (10-30%)	**Scour:**	
☐ 5 – Heavy (30-60%)	☐ Unknown	
☐ 6 – Major (60-100%)	☐ Unlikely	
☐ 7 – Destroyed (100%)	☐ Likely, but cannot see	
	☐ Definitely	

Feature Description:					
1. Approach/ Embankments	☐ None	☐ Minor	☐ Moderate	☐ Severe	Links to the narrative notes and pictures
2. Parapets, Handrail, and Curb Line	☐ None	☐ Minor	☐ Moderate	☐ Severe	
3. Deck	☐ None	☐ Minor	☐ Moderate	☐ Severe	
4. Expansion Joint	☐ None	☐ Minor	☐ Moderate	☐ Severe	
5. Abutments and Wingwalls	☐ None	☐ Minor	☐ Moderate	☐ Severe	
6. Girder	☐ None	☐ Minor	☐ Moderate	☐ Severe	
7. Bearings	☐ None	☐ Minor	☐ Moderate	☐ Severe	
8. Bent Cap and Column	☐ None	☐ Minor	☐ Moderate	☐ Severe	
9. Foundation	☐ None	☐ Minor	☐ Moderate	☐ Severe	
10. Geotechnical	☐ None	☐ Minor	☐ Moderate	☐ Severe	
Other ______	☐ None	☐ Minor	☐ Moderate	☐ Severe	

Recommendations: Choose a recommendation based on the evaluation and team judgment. DDA evaluations should only be recommended with an UNSAFE posting. Provide comments on the recommendations below.

☐ **None** ☐ **DDA (Low Priority)** ☐ **DDA (High Priority)**

Record any recommendations: ______

(QR Code)

Figure 6-9: Sample PDA report generated in the field.

6.7 Interface Design Language

The mobile client interface should be designed and programmed ideally in a way that is portable and runs in all major types of mobile devices, including Android, iOS, and Windows devices. It is recommended that for many of the above functions, the software engineer may consider a web-app development by using jQuery Mobile (https://jquerymobile.com/) or web-based imaging APIs (e.g. PhoneGap). Doing so may lead to touch-optimized and HTML-5 based user interfaces that run in smartphones, tablets, and desktops with different operating systems.

7 SERVER DESIGN AND SERVICES DESIGN

The server development includes design and implementation of critical services that collaboratively realize the functions in the front-end interfaces as shown in the previous sections and figures. As illustrated in Figure 5-1, the basic services grouped based on the directions of the data flow include:

1. Downlink Data Services that provide retrievable information for event information, hazard related mapping products, and other regular mapping products. Downlink data also includes structural inventory and condition data per users' query based on the inventory databases and the structure condition records databases. The databases also include an ACM knowledge database, which provides searchable ACM procedures and sample images of all types of damages for transportation structures and element.
2. Uplink Data Services handle field data receiving and storing including all the structural ACM data for structures and structural elements.
3. Interactive Data Services that deal with field query, interactive ACM data appending, modification, PDA report generation, and other on-demand two-way data services.

The server architecture could be a regular workstation-based server or a virtual instance from a cloud-based infrastructure. It is particularly noted that for modern server design, all the services above are not necessarily implemented within one physical or virtual server. As indicted later, some of these services may be already running in the DOTs. The operating systems may be Windows Server or Linux-based Servers, which are subject to the preferences of the software engineers.

The Simple Object Access Protocol (SOAP) and the Hypertext Transfer Protocol (HTTP) can be used as the basic means for transmission of images, metadata, and web services between the mobile-end Smart App and the server. Several connection types can be considered for data communication between servers and smart devices. The basic connection is via the mobile device's 3G or 4G data network. If 3G/4G networks are not available, a wireless access point ('hotspot') may be established, to which all the mobile devices used by an inspection team are connected.

7.1 Downlink Services

The Downlink Services provide critical data for assisting field-based ACM procedures. Any of this service is on-demand per a simple request from the Smart App user. Therefore, existing databases and server-based mapping products services are critical, which include:

1. Transportation structure inventory databases (e.g., the National Bridge Inventory [NBI]).
2. Transportation structure condition records databases (or maintenance/management databases).
3. General GIS mapping products, such Google Map or OpenStreetMaps.
4. Real-time or near-real-time hazard intensity mapping product (such as the USGS's ShakeMap or ShakeCast; NOAA's Hurricane peak gust wind speed map, etc.). These serve to receive feeds from these federal agencies for newly updated hazard information.
5. Planning-based loss estimation mapping products, which may be based on professional GIS server software (e.g., Hazus-MH can run on an ArcGIS Server)

It is noted that the aforementioned databases or mapping products may exist in the state DOT's inventory. Therefore, there is no need to reconstruct these databases and products in the server sides; the proposed Smart App may be directly interfaced to any of the existing databases or proxies. In the meantime, if these products need to construct in the server side, many of the mapping products may be built using the APIs provided by these products; therefore, these services in the state DOT's servers are only a relay or proxy to the real servers of these products.

7.2 Uplink Data Services

The Uplink Data Services receive regular data points, metadata (a set of information about data), images, and documents from the field. Therefore, a robust DB should be built in the server to accommodate the storing and the querying of these data. Either traditionally used relational DBs (e.g., MySQL) or non-relational DBs (e.g., MongoDB) can be used for this database need for receiving and storing field data. If scalability or fast response is of concern, non-relational DBs may be preferred.

The data structures proposed in Figure 3-2 and Figure 3-3 may be used to design the attributes (data fields) of the databases. It is noted that these suggested variables differ

significantly in nature. Some of the variables can be treated a scalar or string variable; some requires a metadata design in light of its substructure or multi-media types. Some may need modification to accommodate the specific need of the DOT.

7.3 Interaction Data Services

Interactive Data Services provide on-demand services that aim to query the aforementioned databases or even modify/update the field data DB. In the meantime, important services include data aggregation of ACM results from different users for different structures such that they be incorporated in a single GIS layer. Many server-based GIS engines can realize this task.

Other important services include PDA report generation, which is activated once there are ACM results with consensus in a PDA team. The generated PDA report can be viewed by all PDARs and management engineers who supervise the PDA efforts.

8 CROWDSOURCING AND SMARTER FUNCTIONS

8.1 Crowdsourcing Potential

This manual is developed for guiding software engineers at state's DOTs for developing a smart-device based application for trained professionals (i.e. PDARs as defined in this manual). However, incident reporting through social networking and smart apps by the public, namely crowdsourcing, has been recognized in both the research and the practice communities. Therefore, some DOTs may be interested in deploying a reduced version of the developed Smart App above, based on the same back-end services, that is developed intentionally for the general public use. A similar version could also be developed in conjunction with other agencies that may be involved in the emergency response.

The emphasis of this reduced-function app may be on photo- and text-based reporting, which does not need professional training and rely only on the crowd's personal discretion. The benefit of this crowdsourcing approach is that the DOTs may have access to the most rapid damage report from the public, one potential approach to Fast Reconnaissance for emergency events, which can further improve route selection for the PDA. The downside of this approach is the potential of creating 'big data' from the public, which may overwhelm the primary function of the DOTs to respond to these public reporting. Advanced data processing (e.g. big data technologies) may become a necessity, should an agency choose to pursue a crowdsourcing approach.

8.2 Smarter Mobile Functions

Mobile computing devices (e.g., smartphones and devices, wearable computing technologies) advance daily. Therefore, we foresee that many smarter functions can be added in the future to further facilitate assessment efficiency in data collection, sharing, communication, processing, and visualization. Based on the emerging technologies as of developing this manual, the following smarter functions are suggested. Software engineers and DOT's officials can decide to add these functions that may further improve the field assessment efficiency.

1. *Voice recording and recognition*. Voice recording is a traditional technique for field or laboratory experimentation, through which professionals describe and record

observed facts and situations. For example, a touch-based button can be designed in key interfaces of ACM for a system-level structure assessment.
Recorded messages, if in terms of key terms and semantic phrases, can be easily digitally transcribed by using today's natural language processing software or plugins. Therefore, voice recording can be linked to images and reports, enabling the PDARs to focus their senses (e.g., eyes) on the structures and surroundings and complete the form in a hands-free fashion.

2. *P2P tethering to other field devices*. Many digital devices today have P2P data communication capabilities, which include GPS/navigation devices, digital cameras, and label printers. This implies that these devices can be synced with the smart device that runs the SmartTS-ACM. For example, a Bluetooth-enabled camera can automatically push photo pictures to the Smart App-based device. The ACM activities in terms of geospatial locations can be synced with the GPS/navigation devices for aiding route planning (e.g., during driving). A noteworthy smart functionality is field printing of QR codes on adhesive labels (Figure 6-6). The Smart App can directly transmit the QR code to an inexpensive Bluetooth-enabled label printer and has a physical QR code ready in the field for facilitating field posting.
3. Cloud-based computing and advanced data interoperability. Many cloud-based services can be further implemented for added values of field data. Geospatial statistical analysis, even advanced hazard-based modeling, can be implemented in the real-time per the field request. In addition, for enhanced data interoperability, emerging software frameworks, such as the XChangeCore can be integrated with SmartTS-ACM. For example, users can obtain standard GIS products by connecting ArcGIS online or Google Earth to XchangeCore, which interfaces with the databases of the SmartTS-ACM.

9 CONCLUSION

The information presented herein describes important features and considerations for developing a Smart App to support assessing, coding, and marking of highway structures in emergency situations. However, this manual is essentially a starting point to help begin the conversation between structural engineers, emergency responders, and IT professionals to develop a framework to support this and to integrate into each agency's specific database content, IT infrastructure, and data formats. By having this conversation early on, the app will be easier to develop and will be more effective for end users.

REFERENCES

AASHTO. 2011. *Manual for Bridge Evaluation, Second Edition*. American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO. 2015. *Manual for Bridge Element Inspection, First Edition*. American Association of State Highway and Transportation Officials, Washington, D.C.

FEMA. 2011. *Rapid Observation of Vulnerability and Estimation of Risk (ROVER).* FEMA P-154 ROVER CD.

FEMA. 2015a. "ROVER Ready." http://roverready.org/.

FEMA. 2015b. "Hazus." http://www.fema.gov/hazus.

FHWA. 1995. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges.* Report No. FHWA-PD-96-001. US Department of Transportation.

FHWA. 2015. "National Bridge Inventory (NBI)." http://www.fhwa.dot.gov/bridge/nbi.cfm.

Ryan, T. W., J. E. Mann, Z. M. Chill, and B. T. Ott. 2012. *Bridge Inspector's Reference Manual*. Publication No. FHWA NHI 12-049. USDOT, FHWA, Washington, D.C.

Ziering, E. A., and F. Harrison. 2007. *NCHRP Report 576: TransXML: XML Schemas for Exchange of Transportation Data*. Transportation Research Board, Washington, D.C.