Application of System Engineering to a Major ITS Project

Kevin Fehon, B.E., M.Eng.Sc., P.E., PTOE	Timothy Fehon, B.E., B.Comm
DKS Associates 1000 Broadway, Suite 450 Oakland, CA 94607 USA (510) 267 6608 kjf@dksassociates.com	DKS Associates 1000 Broadway, Suite 450 Oakland, CA 94607 USA (510) 267 6643 tjf@dksassociates.com

Abstract

This paper describes the application of system engineering to a major innovative transportation project in the San Francisco Bay Area, the I-80 Integrated Corridor Mobility (ICM) Project. In addition to being one of the first applications of Active Traffic Management (ATM) to a freeway corridor in U.S.A., it is also one of the first detailed applications of formal system engineering processes to a major highway traffic management project in the U.S.A.

Rigorous application of the system engineering process allowed the study team to put a structure around a loosely defined concept and a wide-ranging but incomplete set of system requirements. The study team followed the Federal Highway Administration's (FHWA) "System Engineering for Intelligent Transportation Systems" and also made extensive use of INCOSE's "Systems Engineering Handbook". Using IBM Rational DOORS software allowed the team to decompose the initial concepts, identify the linkages between requirements at different levels and establish a full audit trail so that all elements of stakeholder input could be shown to be adequately addressed.

The paper describes how the gradual education of the stakeholders in the system engineering process was needed to enable the requirements to be fully developed, in particular to allow the study team to differentiate between legitimate requirements and premature design decisions. The stratification of requirements allowed stakeholders at various levels (board member, executive, manager and operator) to understand how their objectives were being met or how they would be able to operate to fulfill their assigned duties.

It is concluded that the FHWA and INCOSE guidelines provide excellent, practical guidance for the development of complex transportation infrastructure systems.

Introduction

This paper describes the application of system engineering to a major innovative transportation project in the San Francisco Bay Area, the I-80 Integrated Corridor Mobility (ICM) Project. In addition to being one of the first applications of Active Traffic

Management (ATM) to a freeway corridor in U.S.A., it is also one of the first detailed applications of formal system engineering processes to a major highway traffic management project in the U.S.A.

ATM involves providing instrumentation and signaling to actively manage the speed, lane availability and accessibility of a highway in real time to maximize the efficiency of the facility. While many highway projects have followed the principles of system engineering in the past, this project has closely followed the structure provided by the Federal Highways Administration's (FHWA) System Engineering Guidebook for ITS (FHWA, 2007). In addition, the definition of requirements and development of a request for proposals (RFP) for system integration has drawn heavily on the System Engineering Handbook (INCOSE, 2009). The entire requirements development process has been managed through the use of the IBM Rational DOORS requirements software (IBM, 2010).

Project overview

The corridor, illustrated in Figure 1, consistently ranks as one of the most congested locations in the San Francisco Bay Area, in both AM and PM peak periods. It includes a 20-mile section of I-80 between the San Francisco-Oakland Bay Bridge and Carquinez Strait, the parallel arterial San Pablo Avenue (part of which is also a State Highway), and the local street connections between I-80 and San Pablo Avenue. The major elements of the project are:

- Area-wide adaptive ramp metering;
- Variable speed limits on the freeway;
- Active lane controls on the most congestion section of the freeway;
- Improved traveler information
- Improved arterial traffic signal operation;
- Route guidance on the arterial roads to guide vehicles diverting from the freeway during incidents; and
- Improved transit information for motorists on the freeway.

The operational concepts that will be employed include:

- Controlling speeds on the freeway as vehicles approach congestion and queuing, to reduce the incidence of crashes;
- Controlling the use of lanes approaching an incident or other lane closure to improve the safety and efficiency of merging traffic and the throughput in the operational lanes;
- Controlling entry onto the freeway in an integrated, real-time and area-wide manner to reduce the extent and duration of congestion;
- Modifying arterial traffic signal operation to accommodate diverting traffic during incidents;
- Providing guidance to motorists who divert from the freeway during incidents to minimize the impact on the arterial roads;

- Provide information to motorists about the availability of parking and transit service to help mode choice decisions in real time.

Figure 1 Project Location and AM Traffic Conditions

The Stakeholders

There are numerous stakeholders with varying degrees of interest and involvement in the corridor's operation. Naturally, it has not been politically wise to characterize the stakeholders as major or minor, nor does it make sense from a system engineering point of view. Every stakeholder has a legitimate perspective and should be able to provide input to the process. It is then through the application of system engineering that competing points of view are rationalized until either an acceptable set of requirements is developed or some stakeholders cease to participate. When this happens, either the project has a smaller scope or the dissatisfied stakeholders oppose the project through processes outside the system engineering activities. While this project has been somewhat controversial and there has been robust disagreement on some aspects of the operational concept, the senior decision-makers have managed to keep the process moving toward the objective of improving the overall level of mobility within the corridor.

The sponsor of the project is the Alameda County Congestion Management Agency. However, the ownership and operation of the system will be distributed among a large number of agencies. The major operator will be Caltrans, which owns and operates the freeway and the signals associated with the ramps. However, the majority of the signals and other facilities on the arterial roads will be owned and operated by ten different local agencies, while some facilities may be owned and maintained by one agency but operated by another. Another group of stakeholders includes agencies that provide services (such as transit and emergency services) that are affected by the operation of the system, although they do not actively participate in its operation. Section 4.1 of the SE Handbook (INCOSE, 2007) provided excellent guidance in identifying and documenting the various users and stakeholders and their needs.

Overview of the Process

The system engineering process has been applied to the project in stages, as the sponsor and other stakeholders have become more familiar with system engineering and also in response to active encouragement by FHWA. An initial Concept of Operations and an accompanying System Engineering Management Plan (SEMP) were prepared by the study team in order to get initial agreement from the stakeholders and provide a vehicle to secure funding from a variety of sources. This was successful to the extent that the project was ranked number one among all projects selected for funding through California's Congestion Management Improvement Account (CMIA). However, although these documents were sufficient to define the project, secure the funding and get the various sub-projects into the appropriate agencies' infrastructure programs, they were not sufficiently well developed to be able to clearly and concisely specify the detailed requirements and develop the necessary systems.

The study team therefore set up a stakeholder input and review process that methodically stepped through the system engineering "winged vee", as specified in FHWA's guidelines and illustrated in Figure 2. This involved detailed revisions and expansion of the Concept of Operation in an iterative process involving both large and small stakeholder workshops, development of requirements in a structured manner and finally developing a detailed RFP for a System Integrator. At the time of writing, the RFP is in draft form being reviewed by the key stakeholders prior to being released for industry review.

The original Concept of Operations needed to be updated to meet the FHWA Concept of Operations guidelines. So the first step we undertook was to take the content of the original Concept of Operations and match it to the FHWA Concept of Operations template document. This process helped clarify what details needed to be discussed and added to the Concept of Operations to develop a complete design. The next step was to decompose the Concept of Operations into simple, single-requirement statements. Each of these was then categorized as a:

- Business requirement;
- User requirement;
- System requirement (either functional or non-functional); or
- Design feature.

Explanation of this process to the client and stakeholders was greatly facilitated by reference to Section 4.2 of the SE Handbook (INCOSE, 2007)

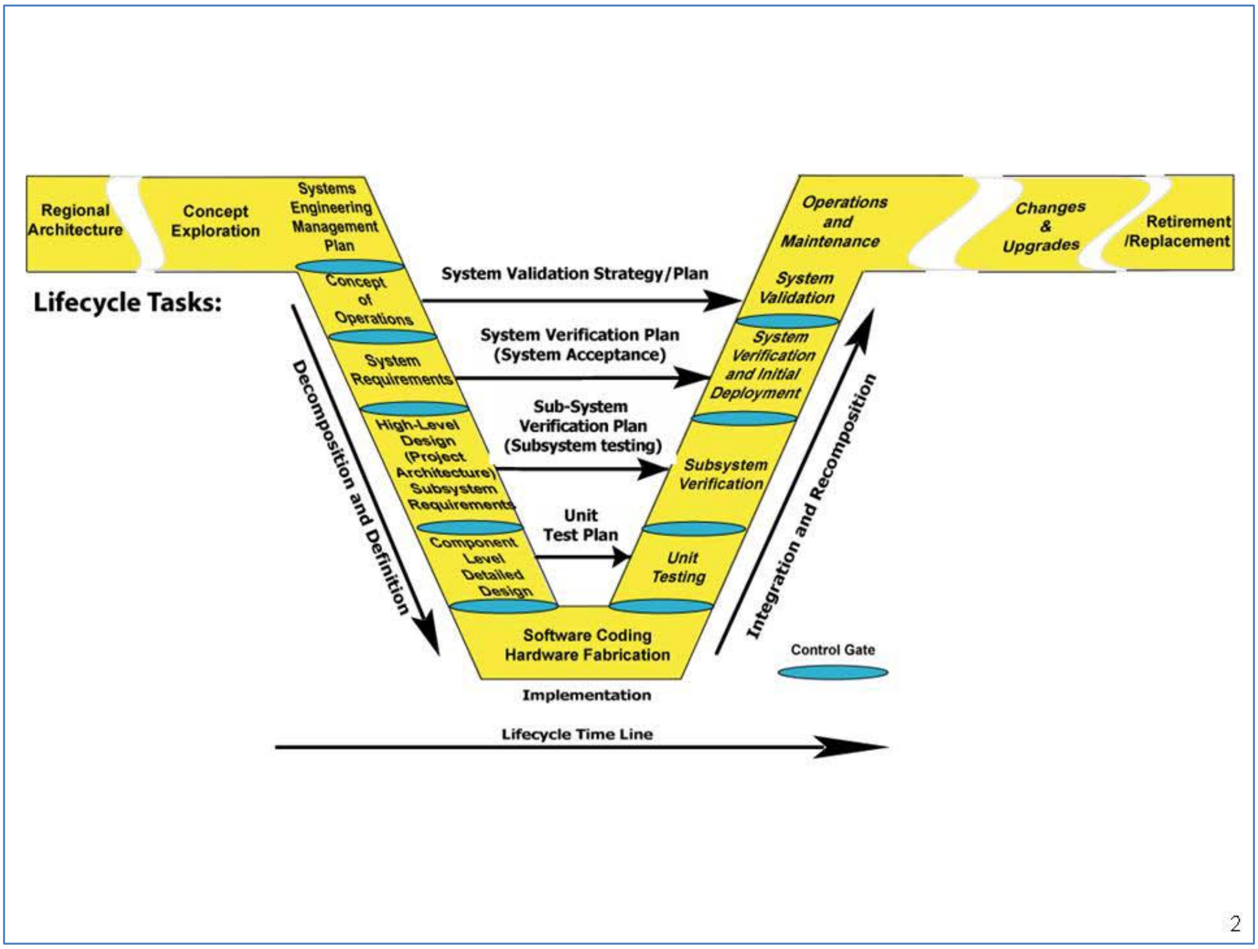

Figure 2 System Engineering "winged vee"

Each design feature was then examined to determine whether it was actually hiding a legitimate requirement, or was simply a design element that had been incorrectly specified as a requirement. These design elements were largely discarded so that the RFP would be specifying the system requirements, not a system design. This process made it clear to the study team that there was much confusion among the stakeholders about what was a requirement and what was a design feature.

Once all the known requirements were categorized, analyzed and refined by the project team, the project team held workshops with stakeholders to refine the requirements further. The first series of workshops focused on revalidating the requirements and resolving conflicts between requirements. The length of time it took to step through these high level requirements reinforced to the project team that there were still significant differing points of view about the project. Slowly, through the process of stepping through each requirement, we were able to build a framework for moving forward.

Secondly, we started addressing the design gaps. This process was best handled in smaller stakeholder focus groups. The project team systematically stepped through each area of the project and discussed how the users foresee the system operation. This was achieved through a review of requirement statements and then a review of different scenarios posed by the project team to the stakeholders. This process of posing then discussing different scenarios provided a context for the discussion to which the stakeholders could relate.

Once a significant number of decisions had been made, the project team redrafted then distributed the Concept of Operations. This allowed the project team to validate the decisions made in the focus group and obtain project buy-in prior to developing the concept further. However there were still enough gaps in the concept that it was not possible to develop the high level design required for the Systems Integrator RFP.

Concept of Operations Refinement

Based on the feedback received for the draft Concept of Operations and the numerous remaining gaps in the Concept of Operations, the team developed approximately 15 additional scenarios covering various operating conditions and introducing numerous fault scenarios. These were then developed into hybrid sequence diagrams, which identified each of the stakeholders involved following each triggering event, and the lines of communications required to enable coordination of their efforts.

Working through those hybrid sequence diagrams with the stakeholders was invaluable in being able to more clearly define the interfaces between other existing systems and the proposed ICM system. It also led to further refinement of the Concept of Operations as operators and owners of other systems clarified what could or could not be achieved within the budgetary and institutional constraints. An example of a hybrid sequence diagram is illustrated in Figure 3.

Based on the feedback received, the project team was able to press forward with refining the concept. Having once again baselined the concept, the project team expanded the requirements and work-shopped more scenarios. Once this process was completed enough times, all aspects of the Concept of Operations were addressed and the project team signed off on the Concept of Operations. The project team was then ready to finalize the high level requirements and develop the System Integrator RFP.

How Requirements Management Software Helped the Process

A key tool that has been used by the project team to manage the project development is the IBM Rational DOORS application. This tool:

- Simplifies the linking of requirements between different requirements levels;
- Simplifies the linking of requirements to test, verification or validation criteria;
- Permits requirement gap analysis;
- Outputs the data into simple documents to share with the stakeholders; and
- Provides a detailed audit trail to assist with quality assurance and quality control

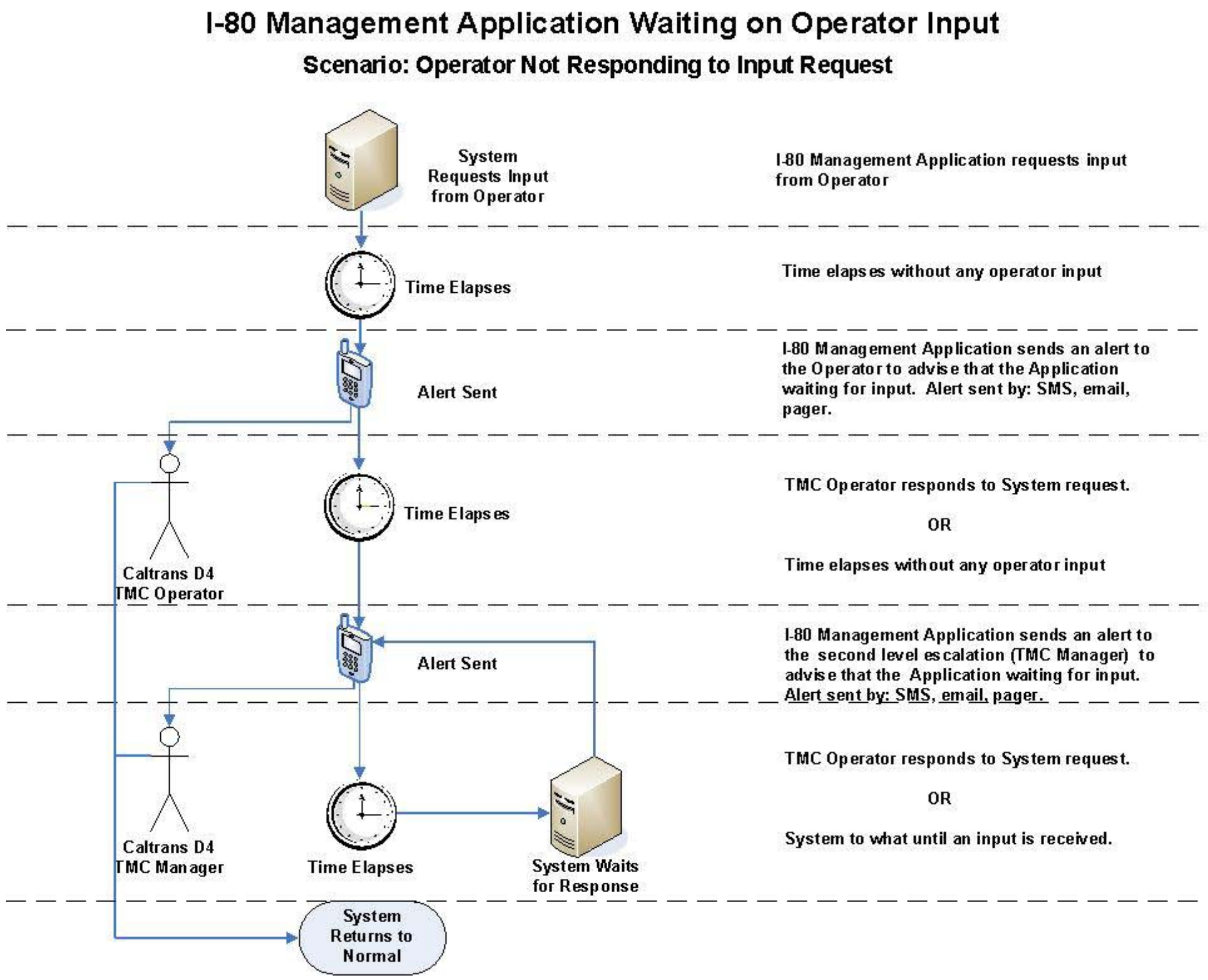

Figure 3 Example Hybrid Sequence Diagram

By using the software the project team worked through the Concept of Operations to document each business, user and system requirement mentioned. Then the team linked the user requirements to business requirements. The business requirements were then reviewed to determine what additional user requirements needed to be documented or elicited from the stakeholders. By using the software the project team could quickly run reports using different views of the requirements to identify the areas that were missing or needing further clarification. These were used to facilitate detailed discussions with the stakeholders. Figure 4 illustrates the relationships between the internal DOORS documents and the project's key deliverable documents.

Issues the Project Team Faced With Implementing Systems Engineering Process

In the early phases of the project the biggest problem that the project team faced was that many stakeholders could not see the relevance of the process. They could not understand the relevance of spending time identifying requirements at such a high level when they already "knew" what the design was. However, through the process of stepping through the requirements and then, in particular, the scenarios, they started to understand why the project team needed to define the project more clearly at the high level. Then the process of going through the detailed list of scenarios described by the project team made clear to the stakeholders the complexity of the system they were wanting, and why the project needed to be specified in such detail.

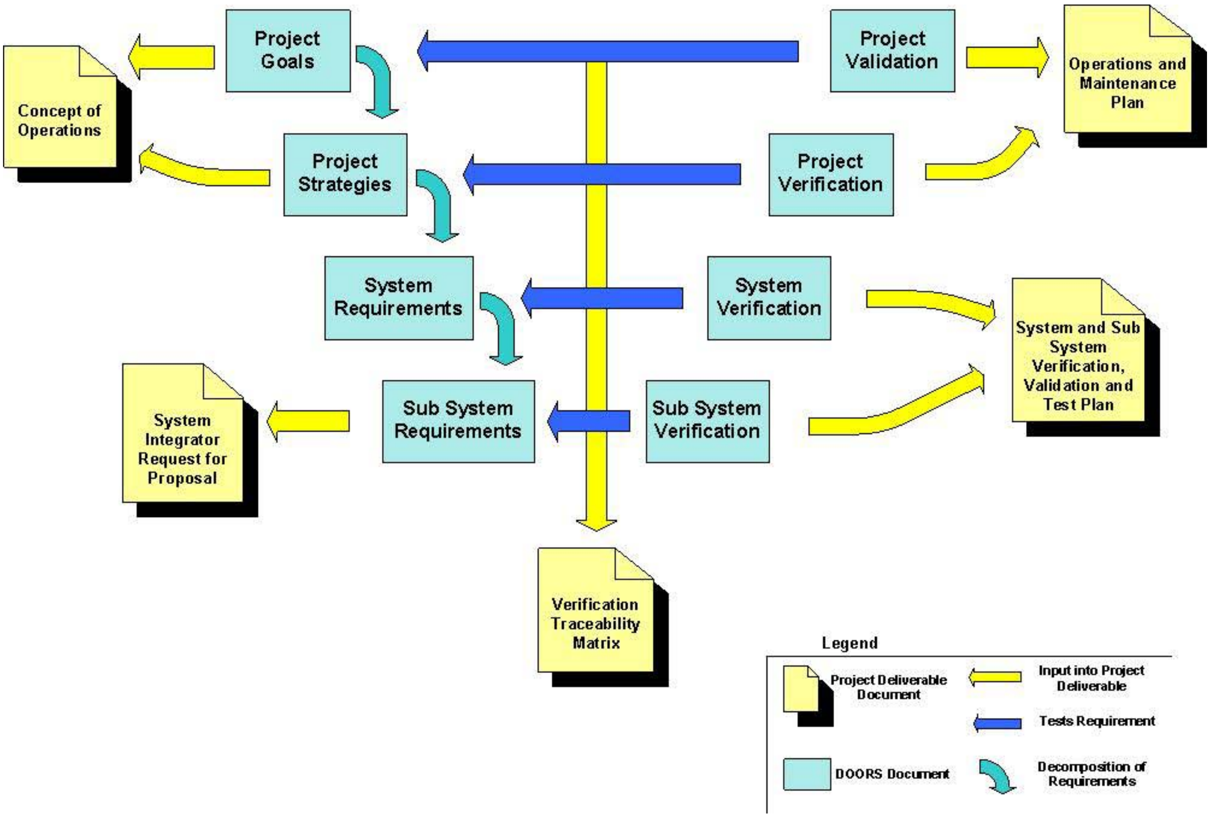

Figure 4 Relationship between DOORS documents and deliverables

Major Benefits Realized by Using the System Engineering Process

Concept of Operations Template

The FHWA Concept of Operations document template provided a great guide for ensuring that all appropriate project details were covered and that all appropriate viewpoints were addressed. By following the template the project team was confident that each facet of the concept was adequately addressed with the stakeholders

Reduces Scope Creep

Decomposing the project into each level of requirements provided a clear definition for the project. Presenting the requirements in a detailed, logical decomposition of requirements that were linked together was quite an “eye-opening” experience for many of the stakeholders. It became clear that some of the features requested by stakeholders, while nice to have from the operator’s point of view, had little to do with the project’s objectives. The great advantage of this process was that it kept scope creep under control and put the onus on individual stakeholders to justify their requests in terms of their agencies’ business requirements.

Catalyst for Policy Decisions

Once the scenarios and context diagrams were prepared by the study team, it was clear to many of the stakeholders that they needed to make decisions about agency responsibilities and inter-agency activities. In many cases, these decisions had been either deferred because they raised issues that the members of various committees did not want to confront, or had not yet been clearly enunciated and seriously considered. These included many relatively minor details that had the potential to derail the project, such as: who would have the authority to switch on certain signs at different times of the day; under what circumstances would an operator in one agency have command and control authority over a sub-system owned by another agency; who would be responsible for maintaining each sub-system and field element, and what performance criteria would be applied to that responsibility.

Defining Project Acceptance

The detailed specification of requirements has significantly enhanced the project team's ability to define test/verification and validation criteria. It also provided a clear framework for assigning the criteria to those parties who are responsible for managing that part of the project specification or design. As engineers are generally risk averse, they would like to assign responsibility for meeting a goal to people further down the design tree. This leads some people to incorrectly believe they have mitigated the risk of either the project not being capable of being built or the completed system not matching the system that the stakeholders desired. This is dangerous for two reasons: subcontractors will not bid on a project or will price the project with a significant premium to account for the project risk over which they do not have control; or the project will not meet the stakeholders' expectations because the subconsultant addresses the risk by modifying the design to meet the requirement but at the expense of other components of the project. Thus the subcontract meets it narrow requirements, but at the expense of the project not achieving its overall goals.

The System Concept

The system concept has now been developed to the extent that an RFP can be issued to a contractor to install the proposed hardware and a system integrator to develop the necessary software. The main features of the system will be:

- Overhead gantries and lane control signals to control the use of lanes when there is an accident, maintenance, construction or other incident that results on one or more lanes not being available;
- Variable speed limit signs to reduce the speed of vehicles approaching congestion or a lane closure, to reduce the likelihood that vehicles will need to make a sudden stop;
- Area-wide adaptive ramp metering, to manage the entries onto the freeway in a coordinated manner that reacts to the actual conditions on the freeway;
- Variable message signs on the freeway to advise motorists of conditions ahead;
- Trail blazer signs on the arterial roads and connecting streets to guide traffic that diverts from the freeway during an incident, to most efficiently return to the freeway downstream of the incident;
- Improved traffic signal systems to allow diverted traffic to be accommodated on the arterials as efficiently as possible; and

- Links from transit agencies to the central TMC to allow relevant transit and parking information to be conveyed to motorists on the freeway.

An example of how the various systems would operate in response to an accident is illustrated in Figure 5.

Conclusions

Rigorous application of the system engineering process allowed the study team to put a structure around a loosely defined concept and a wide-ranging but incomplete set of system requirements. The study team followed the FHWA's "System Engineering for Intelligent Transportation Systems" and also made extensive use of INCOSE's "Systems Engineering Handbook". Using DOORS software allowed the team to decompose the initial concepts, identify the linkages between requirements at different levels and establish a full audit trail so that all elements of stakeholder input could be shown to be adequately addressed.

Documentation of the operational scenarios through hybrid sequence diagrams allowed all stakeholders to understand the impacts on their own operations. The stratification of requirements allowed stakeholders at various levels (board member, executive, manager and operator) to understand how their objectives were being met or how they would be able to operate to fulfill their assigned duties.

Because no infrastructure project is developed in a vacuum, it is rarely possible to start with no existing infrastructure that needs to be retained, with all stakeholders having a complete and clear understanding of their requirements, and then develop a system in a purely linear fashion. As the team progresses through the system engineering process, the stakeholders understand their situation better, change their minds, identify new requirements that hadn't been verbalized earlier; and sometimes new stakeholders are brought into the process. In these situations, the system engineering process clearly identifies scope creep and helps control it while also reducing the risk that requirements remain unsatisfied or unspecified because essential system elements are not provided.

The FHWA and INCOSE guidelines provide excellent, practical guidance for the development of complex transportation infrastructure systems.

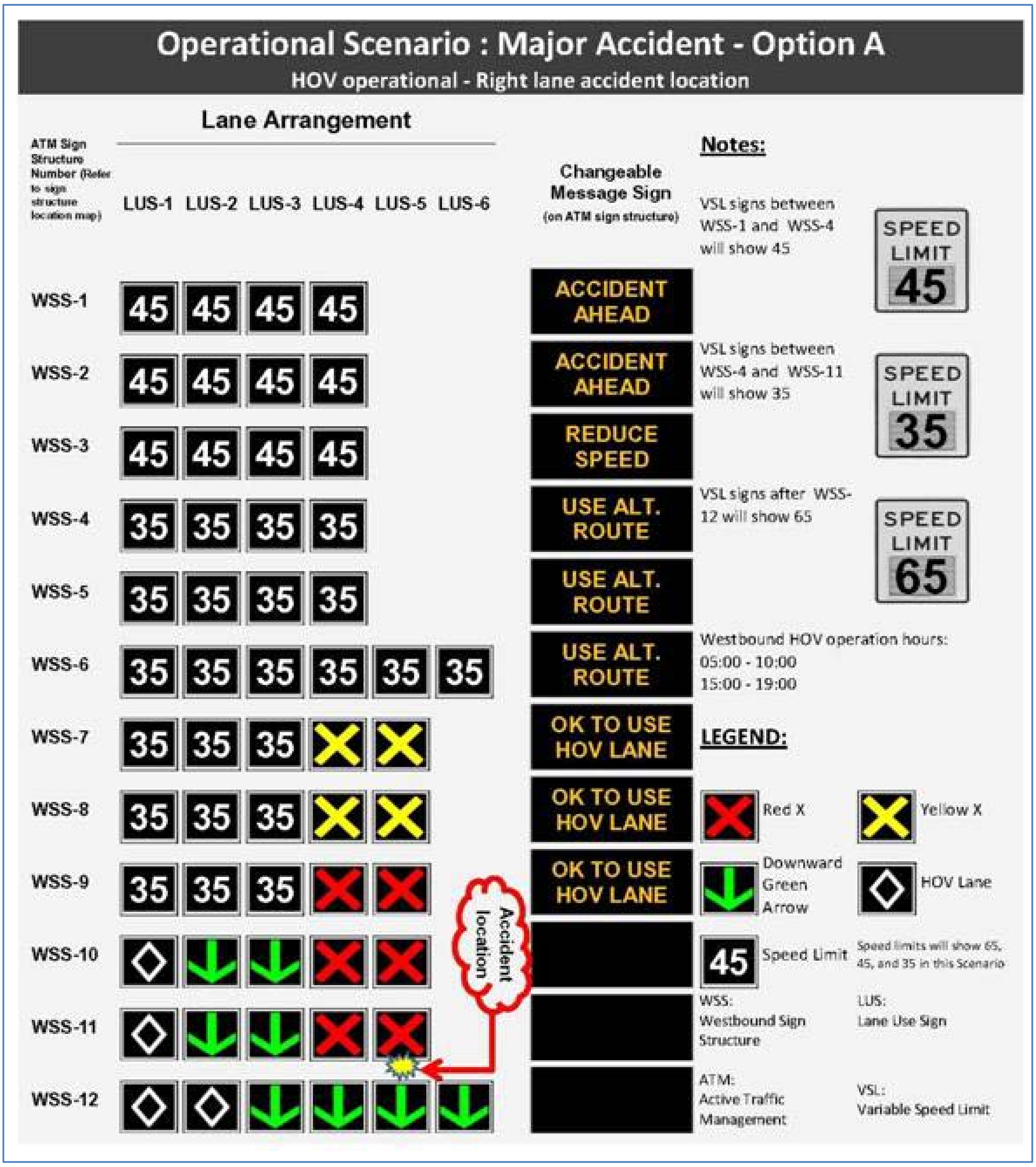

Figure 5 Example system response to an accident

References

FHWA (2007), *System Engineering for Intelligent Transportation Systems, An Introduction for Transportation Professionals*, U.S. Department of Transportation, Federal Highway Administration and Federal Transit Administration.

INCOSE (2007) *Systems Engineering Handbook, A guide for system lifecycle processes and activities, Version 3.1*, International Council on Systems Engineering, Ed by C. Haskins, K. Forsberg and M. Krueger.

IBM (2010), `http://www-01.ibm.com/software/awdtools/doors/`

Biography

Kevin Fehon – Kevin Fehon has 37 years experience in system integration, traffic engineering and transportation planning. He has specialized in the development, implementation and operation of ITS projects in USA, Australia and Asia. He is a nationally recognized expert in adaptive traffic signal systems. Kevin has degrees in electrical engineering, traffic and transportation, and public administration. He is a member of INCOSE and a Fellow of the Institute of Transportation Engineers. Kevin is a Principal at DKS Associates (email kjf@dksassociates.com).

Tim Fehon - Tim Fehon is a highly accomplished Project Manager for software development with nine years' experience delivering complex Information Technology projects within scope, on time and within budget. He has prepared requirements documents and integrated real-time systems for clients in the banking and transportation sectors. He is an excellent communicator and innovative problem solver, with strong project management capabilities. His experience includes project management of complex infrastructure and software projects with a focus on scope management, time management and cost management. Tim is a Senior ITS Engineer at DKS Associates (email tjf@dksassociates.com).