Modeling for Optimal Ambulance Patient Compartment Layout

Deogratias Kibira, Y. Tina Lee, and Mehdi Dadfarnia
Systems Integration Division
Engineering Laboratory
National Institute of Standards and Technology
100 Bureau Drive
Gaithersburg, MD 20899, U.S.A
deogratias.kibira@nist.gov; leet@nist.gov; mehdi.dadfarnia@nist.gov

Keywords: Ambulance design, patient compartment, emergency clinical tasks, ergonomics, safety.

Abstract

About 50,000 ambulances travel on U.S. roads every day. In 2010, there were more than 250 U.S. ambulance crashes that were reported in the news media. Many more ambulances must have been involved in major accidents that did not make it into the headlines. During such accidents, emergency medical technicians (EMTs), who ride in the ambulance patient compartments while caring for patients, are at high risk of suffering injuries. Restraint systems are the first line of defense against injuries or death; however, using restraints makes it difficult to access items and treat the patients. Nevertheless, improving safety necessitates EMTs to remain restrained and to locate most of the items required to perform a wide range of clinical services within arm's reach.

An ideal layout of the patient compartment and location of the equipment, medicine, and supplies should optimize performance of the EMTs while ensuring their safety. To achieve such an interior layout, a requirements analysis of EMT tasks and restraint systems should be carried out. The approach to perform the requirements analysis would include domain expert interviews, literature survey, legacy and emerging ambulance technologies considerations. Alternative layout designs can be developed from the requirements analysis. These designs must target the patient compartment arrangement including the locations of cabinets, sharps disposal, equipment, and supplies. The selection of seat types, seating arrangement, and restraint systems would also be included.

Systems engineering modeling and analysis tools can be especially useful in comparing existing and proposed layout designs against specifies requirements. Human modeling and simulation will be necessary to represent EMT execution of activities in the patient compartment. The outcome of this analysis would lead to recommendations for future ambulance design standards.

1. INTRODUCTION

It is estimated that ambulance crashes in the United States result in one fatality every 10 days and many serious injuries. The cost estimates are more than $500 million every year [Burns 2010]. The majority of these incidents occur during patient transportation. The majority of fatalities are unrestrained emergency medical technicians (EMTs) riding in the patient compartment. Restraining EMTs would increase their safety, but decrease their ability to care for the patient. EMTs have indicated that they would use restraints if they allow some mobility while in transit [Proudfoot et.al. 2007]. The need for mobility depends on such factors as necessary clinical care activities; location of equipment, medicines, and other emergency medical care items; type of seats; and, overall patient compartment layout. Balancing the need for safety with the need for mobility will be vital in future ambulance compartment design.

The First Responder Working Group of the Department of Homeland Security (DHS) identified the lack of design, construction, and performance standards as a critical gap in achieving this balance. The General Services Administration's KKK-A-1822F standard is an ambulance procurement specification; it is not used as design requirements [GSA 2007]. This and other current design guidance documents do not fully address safety alternatives from the perspectives of crashworthiness, performance, and ergonomics. The National Fire Protection Administration's NFPA 1917 standard, on the other hand, does specify the minimum performance parameters, essential criteria, and other requirements for new automotive emergency medical services (EMS) including ambulances. However, it does not address much about the patient compartment [NFPA 2010].

Because of this, many ambulance manufacturers, EMS responders, and researchers are working to design new patient compartments that balance the safety and mobility needs of EMTs. To perform necessary requirements analysis, they use a number of qualitative and quantitative methods. One qualitative method is to solicit information from practitioners, ambulance manufacturers, and government agencies using a survey. Another is to hold a workshop that will verify the outcomes from the survey and gather more information.

A number of quantitative methods are also used. EMT clinical care activities can be simulated to determine performance and design requirements for the patient compartment. Different design concepts and layout configurations can be modeled using computer-aided-design. A number of factors such as EMT activities, EMT statures, seats, restraint systems, cabinets, and placement of items will be varied to determine configurations that would better meet safety and performance requirements. The outcome of such analyses will be a set of design recommendations that will serve as inputs to future ambulance standards.

The rest of the paper is organized as follows. Section 2 reviews literature on emergency medical service (EMS) types, ambulance types, layout designs, and current practice. Section 3 uses systems engineering modeling to compare United States standards with overseas standards to identify the gaps. Section 4 describes the approach to modeling and simulation of EMT activities while section 5 concludes the paper.

2. PROBLEM STATEMENTS

2.1. Background

2.1.1. EMS Types

EMTs perform a range of emergency medical services (EMS) to save the life or ease pain of the patient. EMTs must be certified before they can perform any of these services. In the United States, there are two levels of certification that are common to almost every state: EMT-Basic and EMT-Paramedic [Brouchard 2011]. The types of services provided depend on the condition of the patient. A patient in critical condition needs advanced-life-support services. These services include intravenous cannulation, transcutaneous pacing, cardiac monitoring, and advanced cardiac life support. Only paramedics can perform these services. Other patients receive basic–life-support services or transportation to the hospital. In the United States all of these services can be performed en-route to the hospital.

2.1.2. Ambulance Types

There are three main types of ambulances in service: Type I, Type II, and Type III. Types I and III have a square patient compartment mounted on a chassis. Type I is built on a truck chassis whereas Type III is built on a cut-a-way van chassis. Type II is built on a van type chassis - more like a van with a high roof. Type II is used mainly by hospitals and health departments where the need is usually for transportation of patients to hospital [Metronix 2010]. Depending on location of patient and the hospital, travel times can range from a few minutes to hours. The times are correspondingly smaller for urban than for rural areas. The nature of the call determines the staffing and type of ambulance to be sent.

2.1.3. Patient Compartment Seating and Layout

The interior of the ambulance patient compartment can be laid out in various ways. The traditional layout locates a gurney at or near the center with head of the patient facing inwards; a bench seat that can sit three people on the curb side; a rear facing attendant’s seat, often called the captain’s chair (or airway seat) located at the head end of the gurney; and, a CPR seat on the street side of the compartment. More often, the captain’s seat is off-center with the gurney. The CPR seat is rarely used since it is located in a head strike zone due to the presence of cabinets. The cabinets are attached to the walls for storage of various medicines and other emergency medical care items. Most controls are located at the front and EMTs have to get up to reach them. Figure 1 shows the traditional ambulance layout.

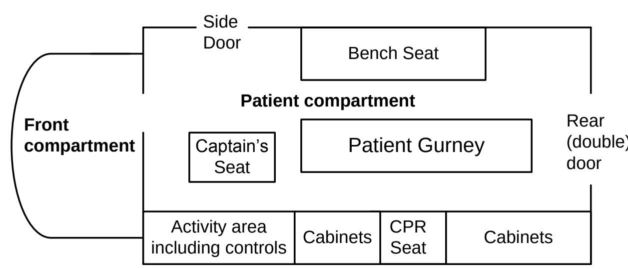

Figure 1. Traditional ambulance layout

2.1.4. Ambulance patient care activities

EMS services are initiated by a call for help, after an incident of serious injury or illness. EMTs perform a range of activities while caring for the patients in transit. The exact activities depend on the severity of the medical problem and responsiveness of the patient. Typically, these activities include checking and monitoring patient vital signs; establishing and maintaining the airway; administering oxygen, pain killers, IV drugs and glucose; and, communicating information to the hospital. To perform these activities, equipment and suppliess are required.

2.2. Problem areas

2.2.1. Ambulance clinical care

Since EMTs work in a moving ambulance and perform physically demanding tasks, they need a work environment that is safe, with occupational hazards minimized or eliminated [Gilad et al. 2007]. Because the patient compartment is a confined workspace, a number of concerns arise. The concerns may be summarized as:

- Patient compartment layout and workflow
- Accessibility of emergency care supplies and equipment
- Equipment mounting

- Seat type and orientation
- Applicability of restraint systems
- Internal and external communication mechanisms

Other concerns include height of the ceiling above the floor, location of the sharps boxes, and height of the gurney relative to the seat (See Figure 5). In case of mass casualties, an ambulance can be configured to carry additional, non-critical patients.

2.2.2. Restraint systems

Seat belts provided to EMTs should offer protection from being thrown around in the compartment but allow access to patients, equipment, and supplies. However, most existing restraint systems rarely do both [Green et al. 2005]. There are a number of restraint types currently available and they include lap belts, lap and shoulder belts, and tethered seat belts. Lap and shoulder belts require seating with the back against the seat back; such a seating position makes it impossible to sit at the front edge to access the patient. The tethered seat belts or mobile restraint systems can allow movement from a seated position and offer some protection - although the wearer would still be swung inside the compartment in case of a crash. EMT seat orientation and cultural practice regarding use of seat belts affect the relationship between restraint systems and safety.

2.2.3. Performance

EMTs must have appropriate equipment and supplies to optimize pre-hospital care. The American College of Surgeons (ACS) Committee on Trauma (COT), American College of Emergency Physicians (ACEP), and the National Association of EMS Physicians (NAEMSP) have collaborated to produce a standard list of equipment for both the United States and Canada. For basic level services that list includes equipment for ventilation, monitoring and defibrillation, immobilization, communication, and obstetrics. There is also a need for bandages, towels, infection control, injury prevention, and other miscellaneous equipment. For advanced level services, the list includes all basic level supplies plus vascular access, cardiac, medications, and other advanced equipment. The full list can be seen in [ACS 2009]. In current U. S. ambulance designs, most of the equipment are carried in interior storage cabinets although some of the equipment can be carried in external cabinets.

3. REQUIREMENTS GAP ANALYSIS

This section describes the requirements gap analysis that was performed using SysML. SysML is a systems engineering tool that supports the analysis, specification, design, verification, and validation of complex systems [Moore et al. 2009]. We examined and compared NFPA 1917 standard with three foreign standards: Alberta Ambulance Vehicle Standards Code, Australian/New Zealand Standard 4535, and British Standards Institution BS EN 1789. The Albert Ambulance Vehicle Standards Code applies to the general construction of ambulances in Canada [Government of Alberta 2010]. The Australian/New Zealand Standard 4535 applies to restraint systems for people and equipment in motor vehicles specifically designed as, or modified and converted into, ambulances for transportation of occupants and equipment [AS/NZS 1999]. The British Standards Institution BS EN 1789 specifies requirements for the design, testing, performance, and equipping of road ambulances used for the transport and care of patients. It contains requirements for the patient's compartment [BSI 2007].

Four SysML diagrams that outline patient compartments' requirements have been created for each of the standards mentioned above. The requirements gaps can then be identified through comparing these diagrams. We used a matrix table that (1) depicts different sets of requirements for the patient compartment and (2) identifies relationships between these requirements to show the comparison of two standards. For example, Figures 2 and 3 are obtained by comparing two foreign standards, the Albert Ambulance Vehicle Standards Code and the Australian/New Zealand Standard 4535, with NFPA 1917. In each matrix table, the row represents the requirements for the patient compartment in the foreign standard that we desire to compare to the NFPA 1917. The column represents corresponding NFPA requirements that may already fulfill a requirement set by the foreign standard. An arrow sign, '↑', is inserted in the table if the NFPA 1917 requirement corresponds to the foreign standard's requirement item. Rows that have not been fulfilled with an 'arrow' essentially exemplify a requirement in the foreign standard that does not have a corresponding equivalent in the NFPA 1917. We note, that this does not necessarily mean that the NFPA 1917 is lacking, since it is possible the foreign requirement does not comply with the American emergency medical services system. In essence, this analysis enables us to identify the areas where one standard might have some strength or advantage over another. For example, the NFPA 1917 lacks the specification for wheelchair accommodation and labeling at each internal compartment.

	3.1 Side Entry Door (From NFPA 1917's Definitions...	1.30.3 Squad bench lids [model organization::Pati...	1.21 Means of Escape [model organization::Patien...	1.4 Patient Compartment Configuration [model or...	1.4.2 Clear aisle walkway [model organization::Pa...	1.31 Patient Compartment Entry Doors [model org...	1.31.11 Door & door latches/hinges load testing [...	1.31.10 Door sealing [model organization::Patient...	1.31.7 Internal lock on each door [model organiza...	1.31.9 Minimum safety glass area per door [model...	1.25.7 Access to patient [model organization::Pati...	1.26 Patient Cot Retention [model organization::P...	2.2 Load Lighting (From NFPA 1917's Low Voltage ...	2.1 Patient Compartment Illumination (From NFPA ...
Alberta Ambulance Vehicle Standards Code (January 20...	1	1	1	1	1	1	1	1	1	1	3	2	1	3
5 Alberta Final Ambulance Vehicle Standards (Jan 2010)	1	1	1	1	1	1	1	1	1	1	3	2	1	3
5.1 Patient Compartment	1	1	1	1	1	1	1	1	1	1	3	2	1	3
5.1.7 Securing of Cots												2		
5.1.7.1 < >												↗		
5.1.7.2 < >												↗		
5.1.5 Auxiliary Seating (dual cot ambulance)														
5.1.5.1 < >														
5.1.5.2 < >														
5.1.11 Door-activated Switches													1	1
5.1.11.1 < >														↗
5.1.11.2 < >													↗	
5.1.8 Action Wall - Medical Control Centre														
5.1.8.1 < >														
5.1.8.2 < >														
5.1.8.3 < >														
5.1.3 Patient Compartment Doors	1		1			1	1	1	1	1				
5.1.3.1 < >			↗			↗	↗							
5.1.3.2 < >									↗					
5.1.3.3 < >	↗													
5.1.3.4 < >														
5.1.3.5 < >								↗						
5.1.3.6 < >										↗				
5.1.3.7 < >														
5.1.3.8 < >														
5.1.4 Patient Compartment Seating											1			
5.1.4.1 < >														
5.1.4.2 < >														
5.1.4.3 < >														
5.1.4.4 < >											↗			
5.1.10 Interior Lighting														2
5.1.10.1 < >														↗
5.1.10.2 < >														↗
5.1.1 Patient Compartment Dimensions				1	1						2			
5.1.1.1 < >				↗							↗			
5.1.1.2 < >					↗						↗			
5.1.9 Patient Compartment Switch Panel														
5.1.9.1 < >														
5.1.9.2 < >														
5.1.6 Squad Bench Lid		1												
5.1.6.1 < >		↗												
5.1.6.2 < >														
5.1.2 Patient Transport Configuration														
5.1.2.1 < >														
5.1.2.2 < >														

Figure 2. Requirements traceability matrix for NFPA 1917 vs. Alberta Ambulance Vehicle Standards Code

	1.8 Equipment Mounting [model organization::Pati…	1.32 Exterior Storage [model organization::Patien…	1.30 Interior Storage [model organization::Patien…	1.7.2 Mounting hangers and supports [model org…	1.4 Patient Compartment Configuration [model or…	1.4.3 Clearance over primary patient area [model…	1.31.11 Door & door latches/hinges load testing […	1.25 Patient Compartment Seats [model organizat…	1.25.7 Access to patient [model organization::Pat…	1.25.8 Child Seating Restraints [model organizatio…	1.25.3 Seat Belts [model organization::Patient Co…	1.25.1 Seat Integrity [model organization::Patien…	1.26 Patient Cot Retention [model organization::P…	1.27 Seat Belt Indication [model organization::Pat…
Australian/New Zealand Standard 4535 (199)	3	2	3	2	1	1	1	3	1	1	1	2	2	1
4 Ambulance Restraint Systems	3	2	3	2	1	1	1	3	1	1	1	2	2	1
4.1 Design and Installation Requirements	2	1	2	2	1	1		2	1	1	1		1	1
4.1.4 Child Restraint Anchorage										↗				
4.1.1 General	↗		↗	↗	↗			↗						
4.1.2 Restraint System for Stretcher Occupant						↗			↗				↗	
4.1.5 Seat Belts											↗			↗
4.1.6 Seating								↗						
4.1.3 Wheelchair Accommodation														
4.1.7 Equipment Storage	1	1	1	1										
4.1.7.2 Labelling Each Internal Compartment														
4.1.7.1 Storage	↗	↗	↗	↗										
4.2 Performance Requirements	1	1	1				1	1				2	1	
4.2.4 Anchorages								↗				↗		
4.2.3 Compartment Doors							↗							
4.2.5 Equipment Restraint Systems	↗	↗	↗											
4.2.2 General												↗		
4.2.6 Restraint System for Occupant to Stretc…													↗	

Figure 3. Requirements traceability matrix for NFPA 1917 vs. Australian/New Zealand Standard 4535

4. DESIGN CONCEPT EVALUATION USING SIMULATION MODELING

4.1. The benefits of modeling

The requirements analysis will be used to develop design options that satisfy those requirements. The design options will be evaluated using a virtual-reality simulation that models EMTs performing a wide range of emergency care activities. These types of simulation have several benefits over traditional physical mockups. First, decision makers can evaluate new designs, layouts, configurations, and systems before committing resources to their acquisition or implementation; thereby reducing the risk of making poor decisions. Second, they can mimic, with high fidelity, the human interactions with the environment, the patient, and the equipment. Third, since they allow humans to enter and interact with a model of the ambulance interior, these simulations can also used in the training of personnel. Fourth, different item placements, tasks, restraint systems, and human performances can be evaluated very quickly at minimal cost. This means that human factors and physical layouts can be modeled and evaluated simultaneously. Figure 4 shows the design concept evaluation process.

4.2. Tasks analysis

Task analysis is the breakdown of work elements, precedence relationships among elements, and a description of how those work elements are to be done. Major tasks performed by EMTs include preparing the ambulance, driving to the patient site, treating the patient at the site, driving the patient to hospital, providing additional care in transit, and delivering the patient to the hospital. Each of these tasks can be broken into work elements. Each such element has a description of constraints and procedures for executing the element. For example, one of the work elements in the treat-patient task is to determine the blood circulation level. The procedure would be to check the heart rate and/or blood pressure. The constraint would be type of stethoscope or blood pressure monitor in the ambulance. The challenge will be to identify EMT tasks and work elements that will form the basis for evaluating different layout designs for the patient compartment including the placement of medicines, tools, and equipment.

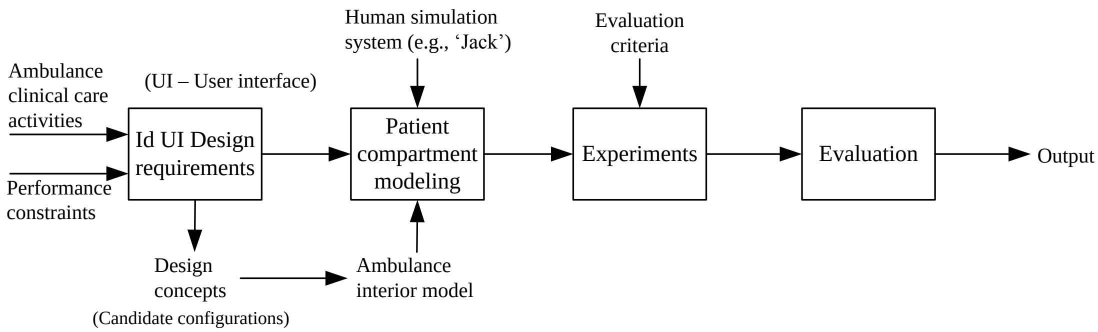

Figure 4. Modeling and layout design evaluation process

4.3. Evaluating different designs

To evaluate different layout designs we need to build and integrate models of the EMT, the patient, and the compartment. To model the EMT, the simulation tool must be able to execute accurately all movements and tasks. For example, it must have a feature to allow the mannequin to grasp/release objects and to detect/avoid collisions with surrounding objects. It must also measure correctly distances of various parts of the human body to the entities in the compartment. This is necessary to establish the viability of various human postures and flexibility of any proposed restraint systems. To build the patient model, we must determine a number of medically critical points such as wrist (for IV insertions), mouth (for ventilation and other procedures), and upper arm (for blood pressure) with a patient lying or sitting on the gurney.

To more accurately duplicate all movements and the actions of limbs and digits, the simulated human body model should be an articulated figure composed of different segments There should also be sufficient control tool and manipulation of the mannequin to represent different postures and positions that an EMT would assume to perform various tasks.

Figure 5 shows two simulated EMTs in a traditional ambulance layout trying to reach a simulated patient's mouth and right arm from seated positions. The mannequins simulating EMTs (one male and the other female of average stature) restrained with lap belts trying to reach and treat a patient. The Figure shows that from a bench seat, it is impossible to reach the right wrist of the patient without unbuckling. But the mouth is readily accessible from the captain's seat.

Figure 5. EMTs reaching different parts of the patient

On the other hand, the conceptual design of patient compartment interiors should be modeled using a 3D graphics modeling tool such as Rhino or AutoCAD and be saved in a format that is compatible for importing into the human modeling software: either as a complete work environment or separate sections. A number of such tools, such as Delmia Ergo, Ramsis from Human Solutions, and Jack from Siemens, do exist on the market.

4.4. Experiments and evaluation

The EMT in the interior of a patient compartment works in a moving work environment. Its safety and the EMT"s performance can be evaluated using virtual simulated environments. Experiments can be carried out in these environments by varying a number of factors. Some of the factors to vary between experiments include:

- Size, gender, stature of mannequins
- Type of ambulance
- Interior dimensions of the ambulance
- The layout of furniture
- Location of equipment, supplies, and medicines
- Clinical care activities
- Restraint systems

5. CONCLUSION

This paper discussed the problems associated with balancing efficiency and safety of emergency medical care in an ambulance. It showed that the existing standards do not facilitate solutions to these problems. The paper advocated the use of systems engineering techniques to identify gaps in those standards and to specify potential requirements for new solutions. These solutions involve new layouts for the patient compartments and new restraining systems for the EMTs. The paper then showed how some new modeling and simulation tools could be used to evaluate those solutions. Robust designs and recommendations for future ambulance design standards are expected to be obtained using modeling and simulation.

DISCLAIMER

Certain commercial software systems are identified in this paper to facilitate understanding. No approval or endorsement of any commercial product by the National Institute of Standards and Technology is intended or implied. And neither does the identification imply that these software systems are necessarily the best available for the purpose.

REFERENCES

1. American College of Surgeons (ACS). (2009). Equipment for Ambulances. http://www.facs.org/trauma/publications/ambulance.pdf

2. Australian and New Zealand Standard (AS/NZS). (1999). “Australian and New Zealand Standard: Ambulance Restraint Systems.”

3. Ballam, E. (2011). “Ambulance Crash Roundup: A review of Emergency vehicle Crashes During 2010.” *EMSWorld*, 40(3), March 2011: pp. 74-75.

4. British Standards Institute (BSI). (2007). “BS EN 1789:2007, Medical Vehicles and their equipment – Road Ambulances.”

5. Brouchard, R. (2011). “The Difference between an EMT and a Paramedic (Not just an ambulance driver).” http://firstaid.about.com/od/emergencymedicalservices/qt/06_EMTBvsP.htm.

6. Burns, L. (2010). “So, you drive an ambulance???” New York Department of Health, Bureau of Emergency Medical Services. http://www.vdh.state.va.us/OEMS/Files_page/symposium/2010Presentations/LMGT-729.pdf.

7. General Services Administration (GSA). (2007). “Federal Specification for the Star-of-Life Ambulance, KKK-A-1822F.”

8. Gilad, I., Bryan, E. (2007). “Ergonomic Evaluation of the Ambulance Interior to Reduce Paramedic Discomfort and Posture Stress.” Human Factors 49(6): 1019-1032 (2007).

9. Government of Alberta. (2010). “Ambulance Vehicle Standards Code: Alberta Health and Wellness.” Emergency Health Services, Health Policy and Service Standards Development Branch.

10. Green, J. D., Moore, P. H., Current, R. S., Yannaccone, J., Day, D., Proudfoot, S. L., Bobick, T. G., Romano, N. T. (2005). “Reducing vehicle crash-related EMS worker injuries through improvements in restraint systems.” *Conference Proceedings XVIIth World Safety Congress, Orlando, Florida.*

11. Metronix. (2010). “Ambulances.” http://www.metronixinc.com/site/ambulances.html.

12. Moore, A., Steiner, R. (2009). *A Practical Guide to SysML*, Elsevier Inc. Page 29.

13. National Fire Protection Association (NFPA). (2010). “Proposed Draft of the NFPA 1917 Standard for Automotive Ambulances 2013 Edition.”

14. Proudfoot, S., Moore, P., Levine, R. (2007). "Safety in numbers: A survey on Ambulance Patient Compartment Safety." *Journal of Emergency Medical Services,* 32(3), (March 2007): 86-90.