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Abstract

This paper describes how modeling and simulation can play a major role in developing standards recommendations for patient compartment layout of automotive ambulances in the United States to improve performance and safety. Acquiring necessary information from relevant stakeholders is shown as a method that can be used to determine user design requirements. The requirements will in turn be used to develop design concepts taking into consideration human interface with the ambulance work environment. The modeling and simulation of clinical care activities in the ambulance can be used to evaluate the design concepts and determine those that would better meet safety and performance requirements.

1. INTRODUCTION

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. It is likely that there are other accidents that did not make it into the news [Ballam 2011]. 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. 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.

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 fatalities are unrestrained EMTs riding in the patient compartment. EMTs have indicated that they would use restraints if it would 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. A uniform performance standard for ambulance patient compartment design and construction is required to balance the needs of safety and performance.

The General Services Administration's KKK-A-1822F standard is an ambulance procurement specification; it is not intended to be used for 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, specifies the minimum performance parameters, essential criteria, and other requirements for new automotive emergency medical services (EMS) including ambulances. However, it does not address much specific to the patient compartment [NFPA 2010].

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

The rest of the paper is organized as follows. Section 2 reviews patient compartment layout designs. Section 3 describes the gap analysis and identifies the needs requirements. Section 4 describes the approach to modeling and simulation of EMT activities. Section 5 concludes the paper.

2. PROBLEM STATEMENTS

2.1. Background

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 the 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. The CPR seat is located in an area where storage cabinets take up space from the ceiling to the level of the seated individual's neck. In the event of an accident the head would be stopped but the lower body would continue being propelled forward. Such a scenario would lead to serious and potentially fatal neck injuries. Therefore, the CPR seat is rarely used. The cabinets attached to the walls store medicines and other emergency medical care items. Most controls, e.g., for HVAC and interior lighting, are located at the front and EMTs have to get up to reach them. Figure 1 shows the traditional ambulance layout.

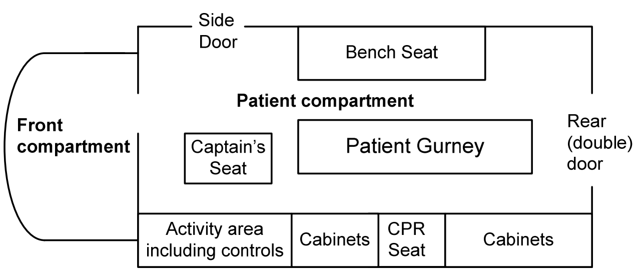

Figure 1. Traditional ambulance layout

2.2. 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 and Bryan 2007]. Because the patient compartment is a confined workspace, a number of concerns arise. The concerns are, mainly:

- Patient compartment layout and workflow
- Accessibility of emergency care equipment and supplies
- 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]. Restraint types currently available include lap belts, lap and shoulder belts, and tethered seat belts. Lap and shoulder belts require sitting with the back against the seat back; such a sitting 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 if an accident should occur. EMT seat orientation and cultural practice regarding use of seat belts affect the relationship between restraint systems and actual 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 found at [ACS 2009]. In current U. S. ambulance designs, most of the equipment is carried in interior storage cabinets although some of the equipment can be carried in external cabinets.

3. REQUIREMENTS ANALYSIS

3.1. Gap Analysis

This section describes the requirements gap analysis that was performed using SysML [Object Management Group 2008]. SysML is a general-purpose graphical modeling language that supports the analysis, specification, design, verification, and validation of complex systems [Friedenthal et al. 2009]. We examined and compared the NFPA 1917 standard with three other standards: Alberta Ambulance Vehicle Standards Code, Australian/New Zealand Standard 4535, and British Standards Institution BS EN 1789. The Alberta 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 by 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 standards; the Alberta Ambulance Vehicle Standards Code and the Australian/New Zealand Standard 4535, with NFPA 1917. In each table, the row represents the requirements for the patient compartment in the 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 standard. An arrow sign, '↑', is inserted in the table if the NFPA 1917 requirement corresponds to the standard's requirement item. Rows that have not been filled with the arrow sign essentially exemplify a requirement in the standard that does not have a corresponding equivalent in the NFPA 1917. Note this does not necessarily mean that the NFPA 1917 is lacking, since it is possible the other standard's 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. All columns are filled indicating that both standards have an equivalent requirement for all sampled specifications in NFPA 1917. However, some rows are not filled indicating an inadequacy on part of the NFPA 1917. For example, the Australia/New Zealand standard 4535 specifies wheelchair accommodation and labeling at each internal compartment currently lacking in the NFPA 1917.

3.2. Design Needs

Through requirements gap analysis as well as ride-along trips, domain-experts interviews, and industry survey, we identified a set of design needs:

3.2.1. Seating

The ambulance seat should allow EMT to:

- easy access to the patient
- easy access to the monitor and controls
- easy access to equipment, supplies, and medicines
- face and eye contact with patient
- ride and perform task safely and ergonomically

The ambulance seats should also satisfy the needs of EMTs from diverse population.

3.2.2. Working Environment

The ambulance working environment should provide the capability to:

- transport and care for more than one patient safely and ergonomically
- allow appropriate lighting, temperature, ventilation, and noise level inside the patient compartment
- allow appropriate communication mechanism for the EMT to communicate with the ambulance driver, hospital, etc.
- supply the required power and power outlets to be used by the communication system, equipment, etc.
- place monitors, controls, equipments, supplies, cot, disposal containers, etc. at appropriate, secure locations for EMT to access easily, effectively, safely, and ergonomically
- appropriate height and room for EMT to move around
- ingress and egress the patient compartment safely

3.2.3. Restraint Systems

The ambulance restraint systems should allow EMT to:

- buckle and unbuckle easily and quickly
- access the patient from a restrained position safely and ergonomically
- access monitors, controls, equipments, supplies, medicines, etc., from a restrained position safely and ergonomically
- perform patient care safely and ergonomically

The restraint systems should also satisfy the needs of

- EMTs from diverse population
- patients from diverse populations

Each of above design needs is continuing to be examined for the development of design requirements. A preliminary set of design requirements is currently being developed. We are also working with the ambulance community to review the completeness and accuracy of the ambulance design needs.

	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
9 Alberta Final Ambulance Vehicle Standards (Jan 2010)	1	1	1	1	1	1	1	1	1	1	3	2	1	3
9.1 Patient Compartment	1	1	1	1	1	1	1	1	1	1	3	2	1	3
9.1.8 Action Wall - Medical Control Centre														
9.1.9 Patient Compartment Switch Panel														
9.1.4 Patient Compartment Seating											1			
9.1.4.1 < >														
9.1.4.2 < >														
9.1.4.3 < >														
9.1.4.4 < >											↗			
9.1.3 Patient Compartment Doors	1		1			1	1	1	1	1				
9.1.3.1 < >			↗			↗	↗							
9.1.3.2 < >									↗					
9.1.3.3 < >	↗													
9.1.3.4 < >														
9.1.3.5 < >								↗						
9.1.3.6 < >										↗				
9.1.3.7 < >														
9.1.3.8 < >														
9.1.7 Securing of Cots												2		
9.1.7.1 < >												↗		
9.1.7.2 < >												↗		
9.1.10 Interior Lighting														2
9.1.10.1 < >														↗
9.1.10.2 < >														↗
9.1.11 Door-activated Switches													1	1
9.1.11.1 < >														↗
9.1.11.2 < >													↗	
9.1.1 Patient Compartment Dimensions				1	1						2			
9.1.1.1 < >				↗							↗			
9.1.1.2 < >					↗						↗			
9.1.5 Auxiliary Seating (dual cot ambulance)														
9.1.2 Patient Transport Configuration														
9.1.6 Squad Bench Lid		1												
9.1.6.1 < >		↗												
9.1.6.2 < >														

Figure 2. Requirements traceability matrix for NFPA 1917 (column) vs. Alberta Ambulance Vehicle Standards Code (row)

	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 (column) vs. Australian/New Zealand Standard 4535 (row)

4. DESIGN CONCEPT EVALUATION USING SIMULATION MODELING

4.1. Design concepts

The analysis of user needs and requirements described in the previous sections will be used to develop design options that satisfy those needs. The development of interior layout design concepts is complex as it is constrained by factors such as space limitations and clinical equipment designs. However, it is not practical or feasible to have a design that fulfills all requirements, which would be an ideal design layout. Therefore, alternative optional design concepts, based on given criteria can be developed that satisfy as many of the requirements as possible. For example, a satisfactory design should locate and affix the monitor, pulse oximeter, and essential drugs closest to the EMT and permit oxygen and IV administration from a seated position. This design may necessitate repositioning of cabinets and redesign of the EMT seat for it to be movable and changeable in orientation. Design concepts to satisfy this requirement may deviate from the traditional layout.

4.2. The benefits of modeling

The design options will be systematically evaluated using virtual-reality simulation models of EMTs performing a range of emergency care activities. This type of simulation has 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 be used in the training of personnel. Fourth, different equipment and supplies 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.

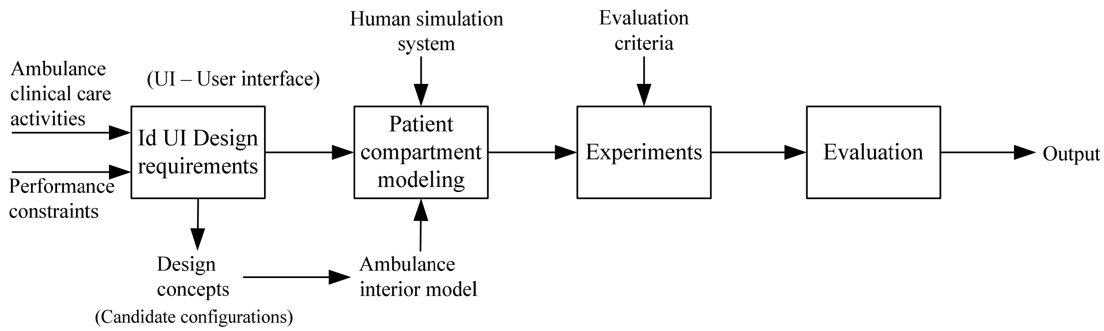

Figure 4. Modeling and layout design evaluation process

4.3. Task analysis

Task analysis is the breakdown of work elements, determination of precedence relationships, and establishment of how the work elements are to be performed. 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 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 the type and location of the stethoscope or blood pressure monitor in the ambulance. The challenge is 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.

4.4. Evaluating different designs

To evaluate different layout designs we need to build and integrate models of the EMT, the patient, and the patient compartment. The conceptual design of the compartment interiors and accessories would be modeled using a 3D graphics modeling tool. Simulating the EMT activities and patient care requires a human simulation tool to accurately depict all movements and tasks. For example, the tool must have a feature to allow the mannequin to grasp/release objects and to detect/avoid collisions with surrounding objects. It must also measure and display distances between two points. This is necessary to establish the viability of various human postures and flexibility required of any proposed restraint systems. To build the patient model, we must determine a number of medically critical points such as wrist, mouth, and upper arm 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, and be easily manipulated to model different postures and positions that an EMT would assume to perform various tasks. The design of the patient compartment requires a compatible format so that it can be imported into the human modeling software tool; either as a complete work environment or as separate sections.

As an example, 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 are simulating EMTs (one male and the other female of average stature) that are 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.

Additionally, Figure 6 shows a configuration for a design concept where a pad attached to the bench seat can allow a seated EMT to slide forward to access the right hand wrist while remaining restrained. The Figure shows that the EMT can reach the wrist in this arrangement. This indicates that if a bench is designed so that it has segmented cushions (life a sofa) placed on a platform that able movement backwards and forwards, flexibility can be improved.

4.5. Experiments and evaluation

The EMT in the interior of a patient compartment works in a moving work environment. Experiments can be carried out by varying a number of factors to evaluate safety and the EMT’s performance. Some of the factors to vary between experiments include:

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

Figure 5. EMTs trying to reach different parts of a patient.

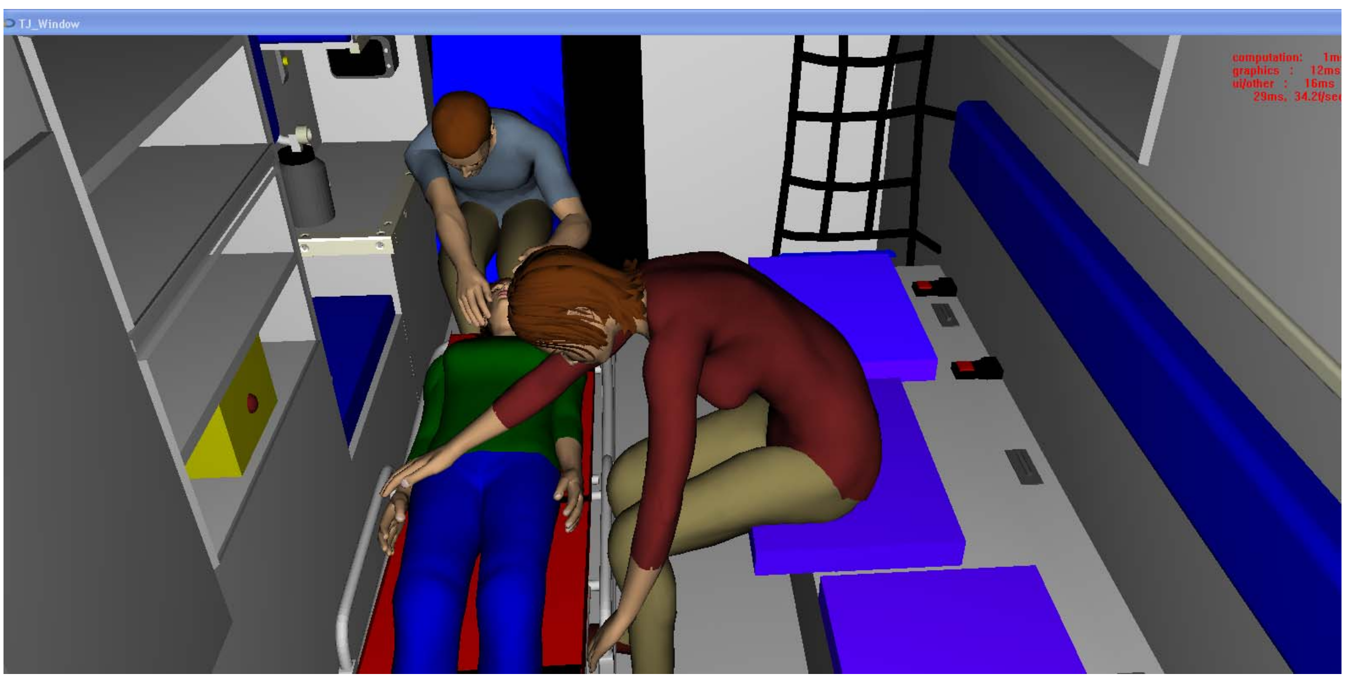

Figure 6. The EMT on a bench cushion placed on a platform that can slide forwards.

5. CONCLUSION

This paper introduces the current inadequacies in design and safety of ambulances and discusses the problems associated with balancing efficiency and safety of emergency medical care in an ambulance. It has shown that the existing standards do not facilitate solutions to these problems. This paper advocated the use of systems engineering modeling (using SysML) to identify gaps in those standards and to specify requirements for new solution designs. It is also shown that modeling and simulation tools could be used to evaluate alternative designs and scenarios to obtain decisions on solutions. These solutions will involve new layouts for the patient compartments and new restraining systems for the EMTs. Robust designs and recommendations for future ambulance design standards can be obtained using a combination of these approaches.

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