Results of a Federated Simulation of Urban Chemical Disaster Response

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ABSTRACT

In late 2005, the Department of Homeland Security selected a multi-University consortium led by the Johns Hopkins University (JHU) to form a National Center for the Study of Preparedness and Catastrophic Event Response (PACER). One of PACER's three-year cross-cutting projects is the construction of an initial integrated M&S framework focused on preparing for the response to catastrophic events. This project is led by the JHU Applied Physics Laboratory, and involves researchers from the University of Alabama at Birmingham, Florida Atlantic University, Florida A&M University, and the Brookings Institution. The first prototype simulation, completed during the winter of 2007-08, was designed to simulate the emergency response to an urban chemical disaster – the release of chlorine from two explosively ruptured railcars – and was developed using the IEEE 1516 High Level Architecture standard.

This paper describes the design of the Urban Chemical Disaster simulation; provides the simulation system engineering considerations that led to the structuring of the flow of simulation execution into a set of slower-than-real-time components (some of which were executed using high-performance-computing equipment) followed by the faster-than-real-time federation executed using personal computers; and discusses the results of the simulation federation integration and demonstration. The components discussed include the wind field generation simulation, the chemical transport simulation, and the insertion of chemical concentrations into the federation; a traffic flow simulation (populated with road network, traffic signal, and demographic information); the dynamic mechanical simulation of the railcar explosion/rupture and the resulting chemical release rate simulation; and the sensing and command/control simulations.

Lessons learned in collaboration will be presented that were derived from the geographically dispersed development of the simulation by the multi-university team. Finally, potential application of the simulation to mission rehearsal by emergency response decision-makers will be discussed.

ABOUT THE AUTHORS

James E. Coolahan is a Program Manager and the Supervisor of the Modeling and Simulation Group in the National Security Analysis Department at the Johns Hopkins University Applied Physics Laboratory, where he also served as the Assistant to the Director for Modeling and Simulation from 1996 to 2001. In his 35 years at JHU/APL, his technical activities have included modeling and simulation, test and evaluation, and the development of oceanographic data acquisition systems. Dr. Coolahan served as a member of the National Research Council (NRC) Committee on Modeling and Simulation Enhancements for 21st Century Manufacturing and Acquisition from 2000 to 2002. He is currently the Principal Investigator for the Modeling and Simulation Integration Framework project being performed as part of the National Center for the Study of Preparedness and Catastrophic Event Response (PACER) for the Department of Homeland Security (DHS). Dr. Coolahan holds B.S. and M.S. degrees in aerospace engineering from the University of Notre Dame and the Catholic University of America, respectively, and M.S. and Ph.D. degrees in computer science from the Johns Hopkins University and the University of Maryland, respectively.

Michael T. Kane is on the Senior Staff of the Modeling and Simulation Group in the National Security Analysis Department at the Johns Hopkins University Applied Physics Laboratory. Mr. Kane has supervised a Software Engineering Section in the Department and has served as the technical lead for projects involving DoD High Level Architecture (HLA) simulations, C4ISR architecture modeling, management information systems and knowledge management. He served as chairman of the Design Steering Committee for the Department of Transportation nation-wide vehicle database management system and as manager of the Advanced Computing and Visualization Laboratory. Mr. Kane holds a B.S. degree in industrial engineering from the University of Pittsburgh, an M.S. degree in operations research from the George Washington University, and an M.S. degree in computer science from the Johns Hopkins University.

Roy P. Koomullil is an Assistant Professor of Mechanical Engineering at the University of Alabama at Birmingham (UAB). Dr. Koomullil received his doctoral degree in Aerospace Engineering from Mississippi State University in 1997. Before joining UAB, he worked as an Assistant Research Professor at the NSF Engineering Research Center (ERC) at Mississippi State University (MSU). Dr. Koomullil's area of expertise includes compressible and incompressible flows, computational fluid dynamics, finite volume upwind schemes on generalized grids, unsteady flow simulation, six-degree-of-freedom (6-DOF) rigid body simulations, overset meshes, and high performance computing. He is a Senior Member of the American Institute of Aeronautics and Astronautics (AIAA) and a Member of the American Society of Mechanical Engineers (ASME).

Evangelos I. Kaisar is an Assistant Professor at the Florida Atlantic University. Prior to joining the University he was a Projects Manager of the Traffic Engineering division in the Maryland Transportation Authority (MdTA). In MdTA, his technical activities included traffic and congestion pricing studies, simulation and modeling, and safety studies. Dr. Kaisar served as a member of the Transportation Research Board (TRB), Committee for Intermodal Terminals, Port Operations, Network Equilibrium and Safety and Security. He is currently the Principal Investigator for the following projects: a) Simulation Modeling project being performed under JHU/APL for the Department of Homeland Security (DHS), b) Intermodal Safety and Security project being performed for the Federal Transit Administration, and c) Congestion impact study for the Port of Miami. Dr. Kaisar holds a B.S. degree in civil engineering from the University of Maryland and National Technological University of Athens, Greece, and M.S. and Ph.D. degrees in Civil Engineering, minor in Logistics, from the University of Maryland.

Kenneth K. Walsh is a Visiting Assistant Professor in the Department of Civil and Environmental Engineering at the FAMU-FSU College of Engineering and also serves as Co-Director of the Wind Hazard and Earthquake Engineering Lab. Dr. Walsh's research interests center around structural vibration control with particular focus in the areas of semi-active control, smart materials for improved structural performance, and vibration absorption and isolation of mechanical systems. Dr. Walsh holds a B.S. degree in Civil Engineering from Florida State University and M.S. and Ph.D. degrees in Civil Engineering from Florida A&M University.

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BACKGROUND

DHS PACER Center Background

In late 2005, the U.S. Department of Homeland Security (DHS) selected a multi-University consortium led by the Johns Hopkins University (JHU) to form a National Center for the Study of Preparedness and Catastrophic Event Response (PACER). The Center is performing research into preparation for high-consequence events, and its research is addressing the technical, systemic, behavioral, and organizational challenges such events pose.

Integrated M&S Framework Project Background

As part of its research program, the PACER Center established several integrated cross-cutting projects. One of these is the construction of an initial integrated M&S framework focused on preparing for the response to catastrophic events. This three-year project, started in the fall of 2006, is led by the Applied Physics Laboratory of JHU (JHU/APL), and involves researchers from the University of Alabama at Birmingham (UAB), Florida Atlantic University (FAU), Florida A&M University (FAMU), and the Brookings Institution. Ultimately, the M&S framework is intended to provide a composable set of simulations that can be used as an aid to decision-makers in training/rehearsal for responses to catastrophic events.

SIMULATION OBJECTIVES AND SCENARIO

Objectives

Planning for the project (Coolahan 2007-1), resulted in six objectives for the project's initial effort, the Urban Chemical Disaster (UCD) simulation. These are:

1. To establish an initial operating capability for the PACER integrated M&S framework.
2. To simulate the release and airborne transport of a dangerous chemical agent in a representative urban area with representative environmental conditions.
3. To simulate sensing mechanisms and command and control strategies in response to the event for several hours after the initial release.
4. To simulate a representative flow of traffic that could result on the urban road network, and realistic traffic routing and control strategies.
5. To execute the simulation for a realistic scenario, incorporating the elements in objectives 2 through 4 above, over a reasonably-sized urban area.
6. To ensure that the simulation federation executes in real time (or faster) on a small set of affordable desktop or laptop personal computers.

Scenario

At the UCD simulation kickoff meeting, held at the FAU Jupiter, FL, campus on February 8-9, 2007, a 2 km x 2 km area in downtown Baltimore was selected as the location for the scenario. Figure 1 is an overhead image of this area, from GoogleEarth. In the lower left of the area is a railroad track that proceeds west to east, south of the football stadium, and then turns to the north, entering a tunnel just southeast of the baseball stadium. This tunnel was the site of a derailment and fire of a train carrying hazardous materials in the summer of 2001, so it was felt that the approach to the tunnel would be a realistic site for the scenario. Coincidentally, a derailment of a train transporting hazardous materials occurred in late November 2007 on the same segment of track selected for the scenario, but there was no release of the hazardous materials.

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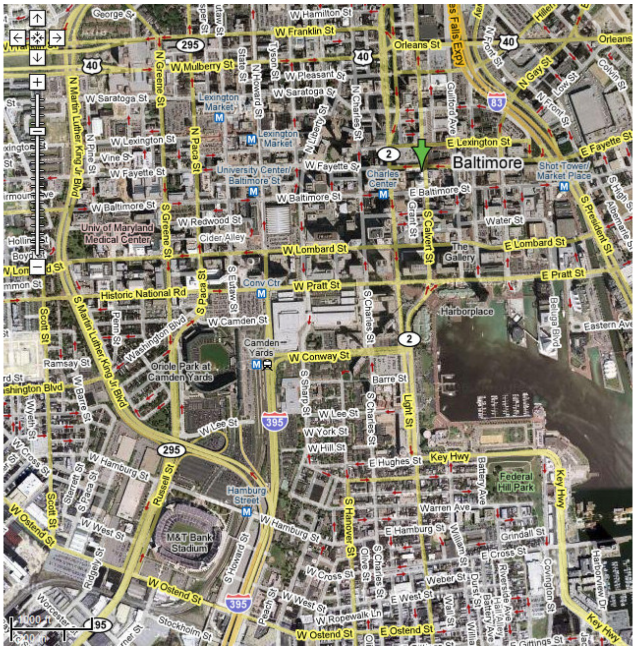


Figure 1. Scenario Location in Downtown Baltimore

The scenario starts at 11:00 am on a clear spring afternoon (April 15, 2008), with an ambient temperature of approximately 75 degrees Fahrenheit, and light (approximately 2.5-knot) winds from roughly a south-southwest direction. A train, which includes multiple railcars containing chlorine, is moving west to east and then turns to the north. A satchel-sized explosive, assumed to be previously placed surreptitiously by a terrorist on one of the railcars containing chlorine near the rear of the train (on the west-to-east segment), is detonated remotely, rupturing the railcar. The train is assumed to stop at this point, but several minutes later, a second explosive located on a chlorine-containing railcar near the front of the train (on the south-to-north segment) is detonated remotely, rupturing it as well.

The hole in each ruptured railcar is of such a size that the chlorine escapes slowly in gaseous form, forming a cloud that gradually moves, driven by the prevailing winds, toward the city center. Alerted by the explosion, local emergency response units follow standard procedures in responding to the event and in assessing the situation. News reports begin to emanate from local TV and radio stations. After assessing the situation, local commanders make the decision to direct that people in the downtown area evacuate. Police in protective gear are dispatched to intersections, and traffic signals are also used to direct traffic away from the affected area. Chemical sensors are placed at selected locations to monitor the chlorine concentrations. The volume of traffic in the downtown area increases as more individuals react (either on their own or in accordance with orders to evacuate) to leave the area in vehicles.

UCD SIMULATION DESIGN OVERVIEW

Figure 2 shows the design for the UCD simulation, including both the non-real-time components that need to be executed prior to federation execution, and the real-time components used during federation execution, along with principal data flows.

The rupture of the railcar is a virtually instantaneous event that serves to trigger the release of the chlorine pollutant, which in turn provides the input for the airborne chemical transport simulation. However, there is no feedback interaction to this simulation component from any of the other simulation components. Therefore, the explosive detonation simulation component need not be part of the federation, and can be executed in advance.

The airborne transport of the chlorine pollutant through the three-dimensional cityscape is a very complicated process. It requires accurate data on the size of all buildings in order to calculate the wind field even in the absence of the pollutant. The transport of the pollutant after its release through the wind field is also a complex process. Execution of similar simulations on other cityscapes has shown that, with current computing capabilities, this function requires a multiprocessor configuration, and cannot be executed in real time. As a result, a design decision needed to be made to divide this function into three steps:

- Generation of the wind field (slower than real time);
- Insertion of the pollutant into the wind field and its transport as a function of time (slower than real time), forming a data file of chlorine concentrations;
- Extraction of chlorine concentrations in real time from the data file.

As a result, the first two steps need to be executed in advance of the real-time simulation federation. Because the second step depends on the release rate of chlorine from the ruptured railcar(s), the chlorine release simulation, although not computationally intensive, also needs to be executed in advance. The remaining functions can be performed in real time (or faster) as part of the federation.

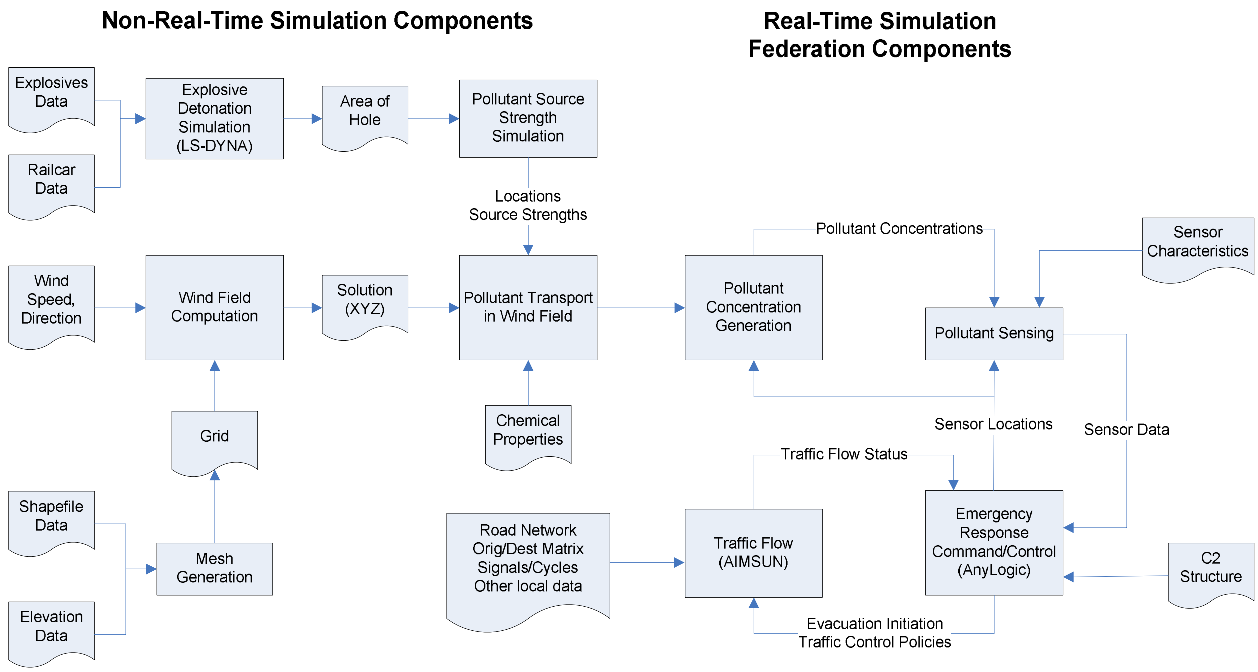


Figure 2. UCD Simulation Block Diagram

NON-REAL-TIME COMPONENTS & RESULTS

Explosive Detonation and Railcar Rupture

The simulation of the explosive detonation and resulting railcar rupture was performed by researchers at FAMU using the LS-DYNA simulation. The railcar model was based on the Department of Transportation (DOT) 105A500W with a gross rail load of 1,169.88 kN (see Figure 3). This particular railcar was selected

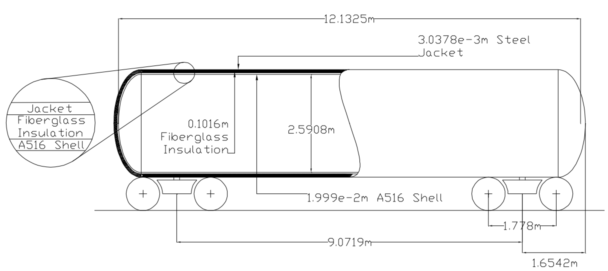


Figure 3. Railcar Schematic

because it represents the most common type of railcar used to transport chlorine in North America (Saat and Barkan, 2006). The car's shell is composed of a 0.1016 m thick layer of fiberglass insulation located between a steel inner shell and outer jacket. The inner shell and outer jacket are made of ASTM A516 grade 70 steel and have thicknesses of 0.0199 m and 0.0030 m, respectively. The total volume of the car's shell is 63.91 m^3 based on an inner shell diameter of 2.59 m and length of 12.13 m.

The railcar rupture scenario presented herein is based on a single individual carrying an explosive satchel containing 6 N (1.3 lb) of dynamite. Dynamite was selected as the explosive material as it is capable of providing a large explosive force for a relatively small amount of material (lightweight), and is readily available throughout the United States. The satchel of dynamite is placed on the top of the railcar, as this location would be the least visible to an observer at the ground level. Simulations were carried out to determine the degree of tank rupture due to the force resulting from the exploding dynamite. These simulations showed that under the conditions described above, the area of rupture resulting from the explosion was 0.196 m^2. Simulation output showing the tank rupture is presented in Figure 4.

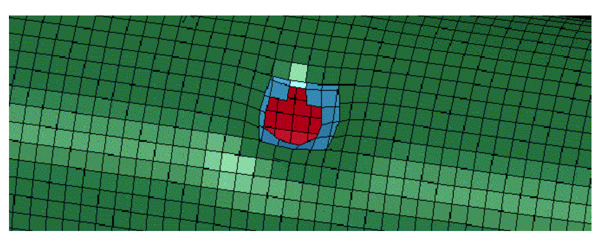


Figure 4. Explosive Detonation Simulation Results

Pollutant Source Strength Computation

The computation of the source strength of chlorine as a function of time as a result of the railcar rupture was performed by researchers at JHU/APL. Source strength was computed using three fluid discharge sub-models (Belore and Buist, 1986): a model of liquid discharge through a tank rupture, a model of the release of compressed gas, and a model of vapor released through a rupture above a boiling liquid.

Atmospheric temperature and pressure, wind speed, the state of the tank and its rupture, and the critical properties of the chemical contained within are used as inputs at each time step to select the appropriate sub-model and to calculate the mass flow rate at that time. Mass balance models are then used to calculate the drop in pressure, the qualities of two-phase flow and the new evaporation rates to define the new state of the system for the next time step. The final outputs are the flow rates at every time step, aggregated together. Figure 5 displays the results of the source strength simulation, showing flow rate as a function of time for a 50-cm diameter hole (the size used in this simulation) and for a 5-cm diameter hole.

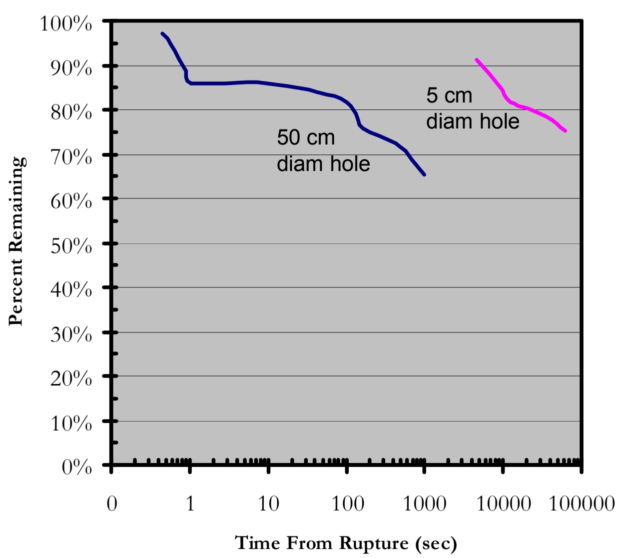
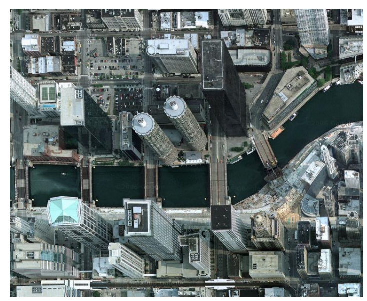


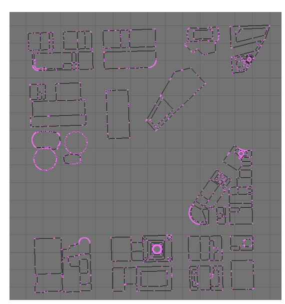
Figure 5. Results of Chlorine Source Strength Simulation

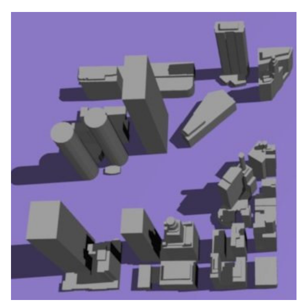
Wind Field and Pollutant Transport

The computation of the wind field and the transport of the chlorine pollutant in the city were performed by researchers at UAB. The first step in the simulation of the wind field and pollutant transport is the creation of the geometry of the city. The cityscape used in this simulation is defined from a Shapefile, which provides the boundaries of the buildings. Shapefile data contains a set of 3D curves, each of which has an elevation associated with it. There are three steps to creating a 3D surface model based on this Shapefile data. First, the curves are triangulated using the Delaunay triangulation method to fill the footprint of the buildings with triangles. Second, the footprint is copied to the height of the buildings. Third, the walls are filled with triangular strips. Examples of a satellite image, Shapefile footprint, and the corresponding 3D building geometry are shown in Figure 6. The resulting buildings are represented as sets of triangulated simple solids. Since the Shapefile defines flat roofs only, domes, slanted roofs, or more detailed roofs cannot be generated. In addition, there may be very small gaps or two solids may be in contact, while a typical mesh generator requires a two-manifold surface model as input (Ito and Nakahashi 2002).



a) Satellite image





(b) Shapefile (c) Extruded Surface

Figure 6. From Satellite Image to 3D Buildings

The second step in the simulation process is the discretization of the domain or mesh generation. An octree-based mesh generation method has been developed because it accepts non-two-manifold surfaces to create volume meshes (Yerry and Shephard 1984). The quality of the mesh is controlled by: 1) mesh type – all tetrahedral, hybrid (hexahedra, tetrahedra and pyramid) and generalized (arbitrary polyhedra); 2) the size and the center of an outer boundary; 3) resolution; and 4) transition speed of mesh density. In the case of tetrahedral mesh generation, node smoothing and face swapping methods are applied to improve the mesh quality. Figure 7 shows a hybrid mesh with 8,918,046 nodes and 12,588,297 elements (6,904,218 hexahedra, 3,896,848 tetrahedra and 1,787,231 pyramids) for Baltimore buildings. The Shapefile for the Baltimore area was obtained from Sanborn. Octants intersecting or inside the buildings are removed during the mesh generation process. Although the surfaces of the buildings become zigzag and small features of the buildings are lost, a volume mesh can be created from non-two-manifold surface models easily and automatically. The number of elements of the mesh can be changed easily using the four parameters described earlier.

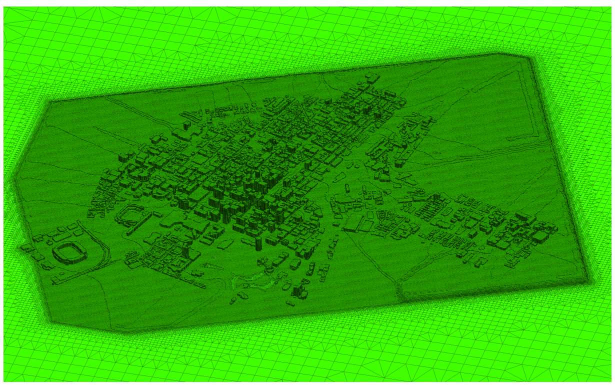


Figure 7. Octree-Based Hybrid Mesh for Downtown Baltimore

The third step in the simulation process is the solution of the equations that govern the air flow. Typical wind speeds within a city fall in the low-speed flow regime and can be considered incompressible. In this study, the artificial compressibility form of the Euler equations are taken as governing equations for the incompressible flow. The effect of viscosity is omitted in the simulation of the wind field. It is well known that the viscous effect is important primarily in the boundary layer region. For the problem of simple geometries or a small domain, resolving this effect is relatively easy with current computer capability. However, it is extremely computationally intensive to resolve the boundary layer of flow around complex geometries and those with disparate length scales; thus, this cannot be an efficient numerical approach for simulating the wind field around numerous buildings and terrains of a city.

Even with the simplification of the inviscid fluid flow, the number of cells required for the wind field simulation for an entire city can be of the order of tens of millions, which necessitates a parallel simulation environment. Keeping this in mind, a parallel finite-volume, cell-centered scheme is developed for the incompressible flow simulation using generalized grids, in which the discretization of the physical domain can be of structured, unstructured or an agglomeration of cells with an arbitrary number of faces (Koomullil and Soni, 1999, 2001). The convective fluxes at the cell-faces are evaluated using Roe's approximate Riemann solver (Roe, 1981). Higher-order accuracy in the spatial domain is achieved using a Taylor series expansion of flow variables. The gradients at the cell center for the Taylor series expansion are estimated using either the Gauss theorem together with a weighted averaging procedure or a least-squares fit of the variables in the neighboring cells. The least-squares system resulting from the latter approach is solved using the Gram-Schmidt method. Limiter functions (Venkatakrishnan, 1993; and Barth and Jesperson, 1989) are added to the Taylor series expansion to avoid the creation of local extrema during the reconstruction process. The flux Jacobian for the implicit scheme is evaluated either analytically, assuming the Roe averaged matrix to be constant, or numerically. Newton iterations are used to improve the temporal accuracy for the case of time-accurate simulations using the implicit scheme (Whitfield 1991).

The block sparse matrix system resulting from the linearization of the governing equations is solved using a symmetric Gauss-Seidel algorithm. The code is parallelized by decomposing the physical domain into a set of smaller regions using METIS (Karypis and Kumar, 1995), which utilizes the graph of the grid to perform the decomposition. The Message Passing Interface (MPI) is used to pass the information across the block interfaces. Figure 8 shows a wind field for the area of downtown Baltimore for a predominant wind of 2.5 kt in the direction of 21.7 degrees east of true north. In this figure, the red color represents high-speed flow and blue represents low-speed flow.

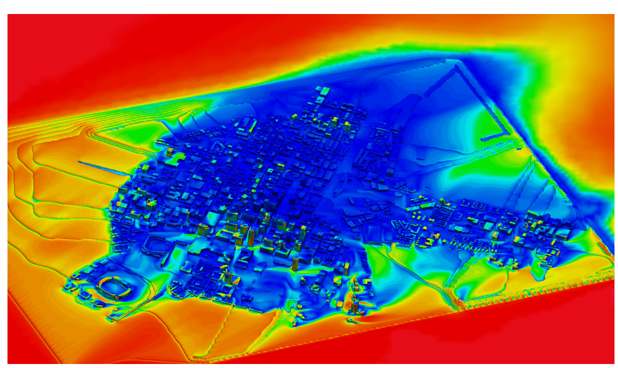


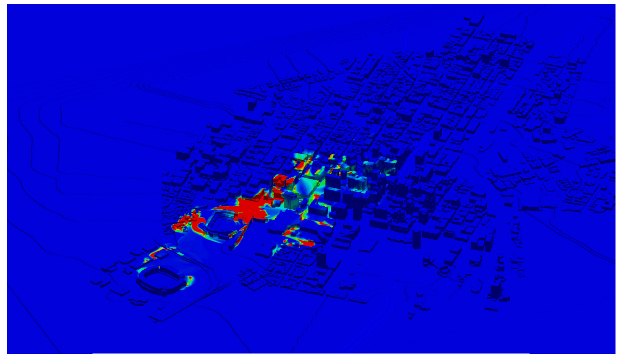
Figure 8. Computer-Simulated Wind Field in the City of Baltimore

The last step in the simulation process is the modeling of the pollutant transport through the urban environment. This is carried out using a general form of a species transport equation, and can be expressed as shown in equation 1,

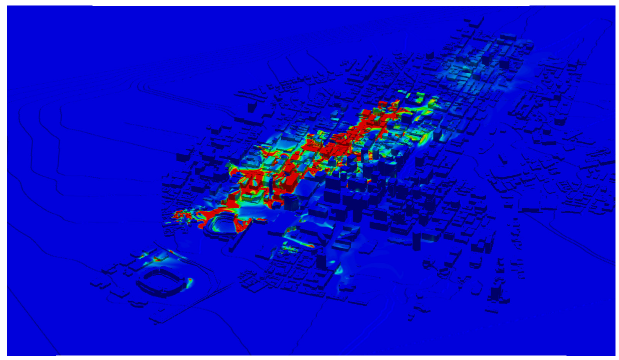
$$\frac{\partial}{\partial t}\int_{\Omega} f dV + \oint_{\partial\Omega} f\vec{U}\cdot\vec{n}ds = \oint_{\partial\Omega} k\nabla f\cdot\vec{n}ds + S \qquad (1)$$

where f and k are species concentration and diffusion coefficients, respectively, and $\vec{U}$ is the velocity vector that is calculated using the wind field simulation. The first term on the left side represents the rate of change of the species concentration inside the control volume Ω, the second term on the left is the rate of species changes due to convection through the control surface, the first term on the right is the diffusion term, and the last term is the source term.

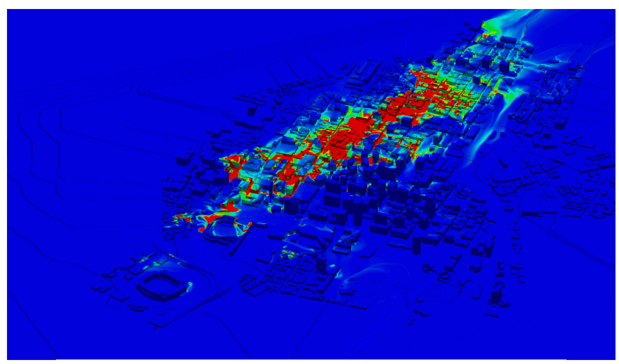
The chlorine release from two railcars as outlined above was carried out using the predicted wind field data. The first release was from the railroad track that proceeds west to east, south of the football stadium, and the second one before entering a tunnel just southeast of the baseball stadium. The wind speed is 2.5 knots and the direction is 21.7 degrees east of true north. The concentration of chlorine at different times after the release is shown in Figure 9. The red color represents the area where the concentration is above 0.008 kg/m^3, which is hazardous for humans exposed to that concentration for more than 10 minutes.



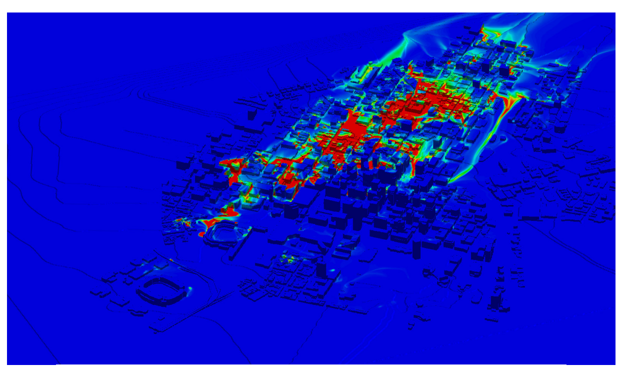
(a) One hour after initial release



(b) Two hours after initial release



(c) Three hours after initial release



(d) Four hours after initial release

Figure 9. Chlorine Concentration at Ground Level at Various Simulation Times

REAL-TIME COMPONENTS & RESULTS

Federation Overview

The real-time UCD simulation federation consists of the simulation components shown on the right side of Figure 2, along with a recorder component and a RunTime Infrastructure (RTI) compatible with the High Level Architecture (HLA) specification. As none of the selected simulation components previously had an HLA-compliant interface, there was freedom in selecting between the original Department of Defense HLA 1.3 standard, and the Institute of Electrical and Electronics Engineers (IEEE) 1516 HLA standard. The IEEE standard was selected for use.

HLA interfaces were constructed for all of the simulation components, and the federation was successfully integrated and two "runs for record" were performed at JHU/APL on January 17-19, 2008. The "real-time" simulation federation was actually able to be executed 8-10 times faster than real time.

Pollutant Concentration Generation

The real-time generation of chlorine pollutant concentrations in three dimensions as a function of time was done by researchers at UAB, using the results of the computations of the wind field and the pollutant transport done in advance.

Detailed modeling of chemical, biological, and radiological (CBR) agents through an urban area is a computationally intensive process and is not practical for real-time implementations. In order to incorporate the simulation results into real-time emergency management simulations, prediction of pollutant transport in, or faster than, real time, while maintaining a certain level of accuracy, is required. Therefore, a set of pollutant concentrations in the City of Baltimore was pre-computed based on the prevailing wind conditions as outlined above, and saved in a database where they could be accessed and utilized by the real-time simulation federation. These concentrations were saved at time intervals of one minute, and a linear interpolation algorithm was used in the real-time simulation component to retrieve the cached chlorine concentrations to provide an estimated path of chlorine through the city.

Pollutant Sensing

The modeling of pollutant sensors was performed by researchers at JHU/APL using a modified version of a commercial sensor monitoring and response product. JHU/APL had the Chemical, Biological, Radiological, and Nuclear (CBRN), Early Warning and Decision Support System, SENTRY™, modified by the developer, ENSCO, Inc., to accept simulated sensor data from the pollutant concentration generation simulation. The sensor simulation requests pollutant concentration data from the pollutant concentration generation simulation at locations that represent point-detect sensors in the field, which may be deployed "on-the-fly" by the command and control simulation. Sensor capabilities include identification of toxic substances and comparison of concentration levels to toxicity thresholds. Sensors require a minimum dwell time and can generate false positives. In an urban environment, diesel exhaust can interfere with sensor accuracy. The sensor simulation publishes results to other federates. Sensor results can be used to identify and monitor toxic substances, establish a safety perimeter, and measure the effectiveness of decontamination efforts.

Emergency Response Command and Control

The modeling of the command and control (C^2) of emergency response actions was performed by researchers at JHU/APL, using the AnyLogic version 6 simulation tool. The C^2 simulation supports analysis of strategic, tactical, and operational planning and activities, including deployment of resources and maintenance of situational awareness during the toxic industrial chemical spill and possible emergency evacuation of parts of the city.

DHS documents provide guidelines for emergency command and control. The National Response Framework (NRF) establishes a single, comprehensive approach to domestic incident management. The National Incident Management System (NIMS) provides a systematic approach for agencies to respond to and mitigate the effects of incidents in order to reduce the loss of life, property, and harm to the environment. NIMS requires that jurisdictions adopt the Incident Command System (ICS), a standardized, on-scene, all-hazard incident management concept, as a condition of receiving Federal preparedness funding. The following objectives for the C^2 simulation were derived from the emergency response federal planning guidelines:

- Simulate realistic command and control strategies for responding to the catastrophic event for several hours after the initial release;
- Select strategies and provide commands to other simulations for simulated implementation of the strategies;
- Simulate evacuation of the affected area by interfacing with the traffic control simulation;
- Simulate situational awareness available from various sensor technologies and sensor deployments; and
- Control the simulation clock for real time or faster operation of the federated simulations.

A constructive simulation was used to model the incident from the initial reporting to the 911 communications center through several hours of incident response activities.

The sensor simulation interface enables the simulated deployment, activation, deactivation or movement of sensors at arbitrary locations. The C^2 simulation maintains a representation of the Incident Commander's situational awareness based on sensor data and field reports. The C^2 simulation subscribes to the pollutant concentration information published by the sensor simulation.

The C^2 simulation obtains traffic flow status of evacuation routes from the traffic simulation. It communicates with the traffic simulation to:

- Initiate evacuation plans for parts of the affected area;
- Prevent traffic from crossing within the safety perimeter; and
- Dispatch police officers to traffic control locations.

The traffic simulation interface enables simulation of the deployment of police at traffic control locations specified by the city evacuation plan. After a simulated delay, the C^2 simulation instructs the traffic simulation to modify traffic behavior at intersections to simulate the switch from the current traffic signal control to police-controlled timing. The C^2 simulation can instruct the traffic simulation to alter the parameters of traffic flow along the key evacuation routes. The traffic simulation interface supports this by enabling the C^2 simulation to invoke traffic "policies" that switch flow to simulate changes in the incident environment, e.g., the toxic chemical plume passing across an evacuation route. The C^2 simulation displays the status of the evacuation on its situation map and can get traffic flow status for any road segment from the traffic simulation via the HLA RTI used for the simulation federation. The current implementation changes the color of the evacuation routes to red or yellow on the C^2 situation map to reflect traffic congestion. Figure 10 shows a situation map, with evacuation route manning, produced as part of the simulation.

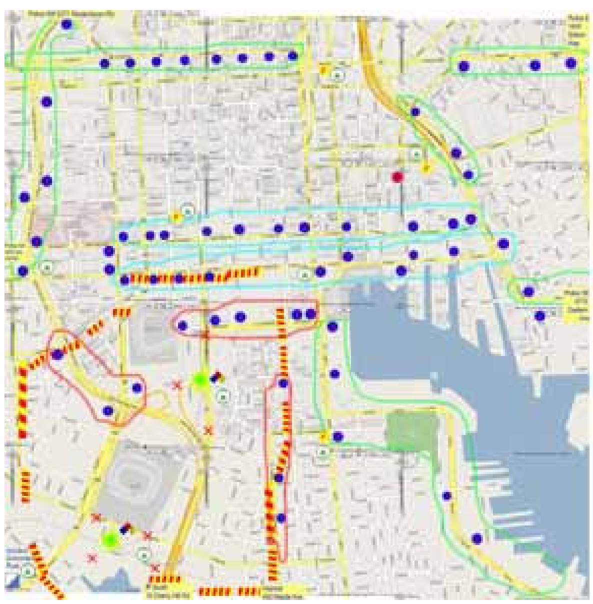


Figure 10. Situation map with evacuation manning

Traffic Flow Modeling

The modeling of traffic flow in response to the emergency response actions was performed by researchers at FAU using the AIMSUN NG 5.1 simulation tool. AIMSUN is a micro-simulator that also allows for mesoscopic and macroscopic views of real-time information. It can display traffic flow, delay time, queue time, congestion, etc., in real time for each road section in different formats

Traffic Network Design

The traffic network geometry for the simulation was designed from 2D Shapefiles. These Shapefiles were augmented with Google Earth satellite images to capture the minute details of the existing road configurations. From here, these 2D images are then extruded and used in the generation of the 3D network. The completed traffic model of the downtown Baltimore business district has 475 sections and 156 intersections. The network area is bounded by the following roads: US 40, I-83 and I-395. The network as created in the simulation is shown in Figure 11. Pre-timed traffic signals dominate much of the downtown business district intersections. The traffic demand is simulated using origin-destination matrices. This traffic information was created using traffic counts provided by the Baltimore Metropolitan Council, in addition to the current population census data.

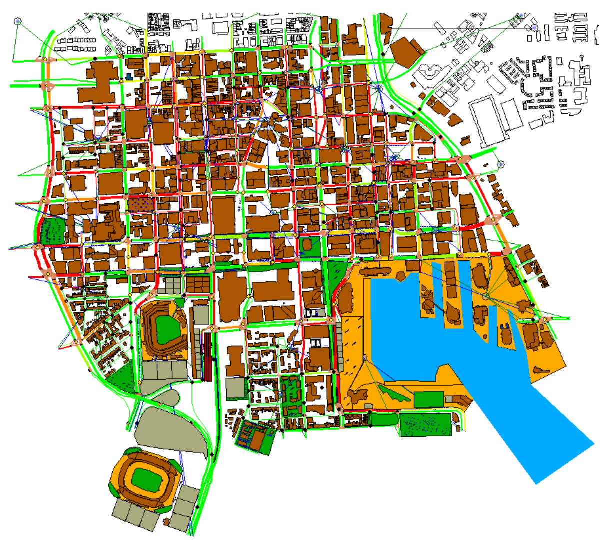


Figure 11. 2D Road Network as Created in AIMSUN, with Colorized Traffic Flows

During the simulation federation execution, AIMSUN communicated with the C^2 simulation as discussed in the previous section, and generated traffic flow information in response to the traffic control policies generated by the C^2 simulation.

Evacuation Methodologies

In addition to the real-time simulation execution, which implemented a specific evacuation strategy, several additional evacuation strategies were evaluated. These evacuation strategies stem from an extensive literature review, previous evacuation case studies, and the existing evacuation plan for Baltimore. From this, six methodologies were evaluated: Nearest Two Exits, Police-Assisted, Staged, Staged with Police-Assisted, Contraflow, and Staged Contraflow. These methodologies were compared to one another using pertinent measures of effectiveness (MOEs), such as Traffic Flow, Mean Speed, Relative Travel Time, and Delay Time. Each methodology was then simulated using three separate evacuation times, resulting in 18 different trials.

Traffic Flow Results

AIMSUN has the ability to display the traffic conditions at the mesoscopic level in different colors such as red, yellow, and green, as shown in Figure 11. The different colors represent different levels of service (LOSs) on the road network. The red color represents congestion and the green color represents free flow speed (not congested). In addition, based on the results of the simulation, it is evident that different methodologies provide various results. For instance, according to the applied methodologies, Contraflow and Staged Contraflow evacuation strategies provide the best results for the case study.

These two strategies dominate every MOE and have the highest LOS values. However, Contraflow strategies require many well-trained and equipped personnel. They also require time to organize and dispatch personnel to the appropriate destinations. Staged strategies are flawed because they require people to ignore the basic instinct to flee. Once a zonal evacuation is ordered, people from all the zones will begin to evacuate despite being directed otherwise. Meanwhile, police-assisted strategies, however practical, showed limited benefit in the results.

An example of these results is displayed in Figure 12, as relative travel time. This chart displays the relative effectiveness of each strategy's total travel time when compared to the control. The control is taken to be the Nearest Exit strategy, because it is the most likely scenario to occur. It is seen that the Police-Assisted strategy shows a nominal increase when compared to the control scenario with regard to travel time. The Staged and Staged Police-Assisted strategies show an increase of about 12% and 17%, respectively. This is the result of allowing specific zones access to the entire capacity of the network at once. The Contraflow and

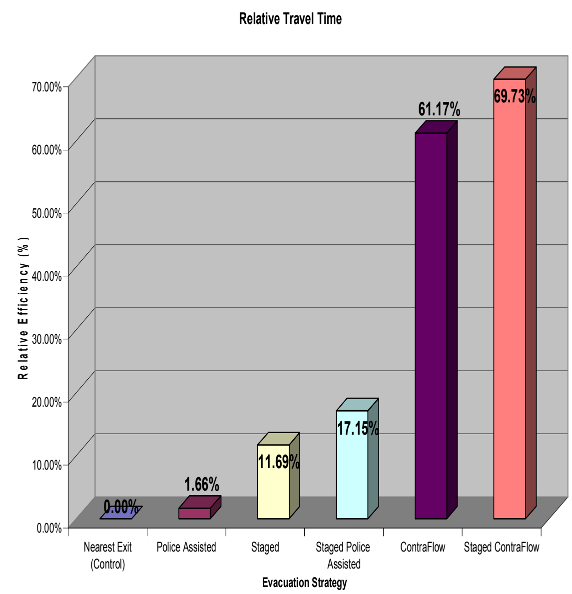


Figure 12: Relative Travel Time MOE Chart

Staged Contraflow strategies result in the best relative evacuation, with 61% and 70%, respectively.

SUMMARY OF LESSONS LEARNED

Although there were several technical challenges, from the outset, it was felt that the most significant challenge faced by the project was that of getting four separate university partners, each with separate funding streams, and in widely dispersed geographic locations, to collaborate in the development of a unified simulation that had to execute in an integrated fashion in real time or faster over a local area network, with only one year of development time. There were three key lessons learned from the project, only one of which was technical:

1. The professional willingness of the team members to work together toward a common goal with a unified schedule was a primary ingredient to the success of the collaboration.
2. The use of quarterly face-to-face team meetings, and the rotation of the location among the four partner universities, helped to build camaraderie among the team members, which facilitated the bi-weekly teleconferences to discuss progress.
3. The availability of the HLA simulation tools to facilitate interoperability, and the use of a core set of experienced staff to develop the HLA interfaces for all of the real-time components, added efficiency to the integration process. Only one "pre-integration" event was needed at FAU, and the final integration took only two days.

POTENTIAL APPLICATIONS

The potential uses of the UCD federation fall into the three functional areas of training/mission rehearsal, analysis of alternatives, and system acquisition.

The training/mission rehearsal area is envisioned to be the primary use of the UCD simulation federation. This is the reason that objective six deals with the need for real-time execution. Within this functional area, there could be two specific uses: seminar gaming to perform course-of-action development, and decision-maker training for specific chemical release scenarios.

In seminar gaming, JHU/APL has long used its Warfare Analysis Laboratory (WAL) to host groups of diverse stakeholders in specific problem areas to address potential courses of action in various scenarios. WAL capabilities include four independently controlled projection screens that can display visualizations of simulations, briefing materials, numerical data, surveys, etc., and an integrated 53-laptop electronic seminar support system for exchanging and capturing participants' comments, and exercising decision-support software. Although the WAL was originally established to address military problems, it was also used in post-9/11 planning by Baltimore City to address potential responses to future catastrophic events, with in-person participation by many government officials, including the mayor, and representatives of non-governmental organizations such as local hospitals.

Once a course of action has been established for a specific scenario, the UCD simulation federation could then be used to train first-responders for preparedness purposes. The UCD simulation federation could also be used to support analysis of alternatives and related system acquisition decisions. For example, a postulated automated traffic signal control system could be overlaid on the traffic flow simulation, and various strategies could be analyzed to determine optimal signal timing under various conditions.

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