

Application of Visualization and Simulation Program to Improve Work Zone Safety and Mobility



Final Report
January 2010

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
the Smart Work Zone Deployment Initiative
and
the Iowa Department of Transportation

About the SWZDI

The goal of the Smart Work Zone Deployment Initiative is to improve the safety and efficiency of traffic operations and highway work by investigating better ways of controlling traffic through work zones. The SWZDI is part of the Transportation Pooled Fund Program, Study Number TPF-5(081). The project is administered by Iowa State University's Institute for Transportation. The lead agency is the Iowa Department of Transportation.

Disclaimer Notice

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the sponsors.

The sponsors assume no liability for the contents or use of the information contained in this document. This report does not constitute a standard, specification, or regulation.

The sponsors do not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Non-discrimination Statement

Iowa State University does not discriminate on the basis of race, color, age, religion, national origin, sexual orientation, gender identity, sex, marital status, disability, or status as a U.S. veteran. Inquiries can be directed to the Director of Equal Opportunity and Diversity, (515) 294-7612.

SWZDI

Smart Work Zone Deployment Initiative

Report Title		Report Date: 2010
Application of Visualization and Simulation Program to Improve Work Zone Safety and Mobility		
Principal Investigator Name Strong, Kelly Affiliation Iowa State University Address 454 Town Engineering Building Iowa State University Ames, IA 50011 Phone (515) 294-1460 Fax (515) 294-3845 Email kstrong@iastate.edu		Vendor Name and Address «Vendor»
Author(s) and Affiliation(s) Kelly Strong, Iowa State University Manop Kaewmorachoen, Iowa State University		
Supplemental Funding Agency Name and Address (if applicable)		
Supplemental Notes		
Abstract <p>A previous study sponsored by the Smart Work Zone Deployment Initiative, “Feasibility of Visualization and Simulation Applications to Improve Work Zone Safety and Mobility,” demonstrated the feasibility of combining readily available, inexpensive software programs, such as SketchUp and Google Earth, with standard two-dimensional civil engineering design programs, such as MicroStation, to create animations of construction work zones. The animations reflect changes in work zone configurations as the project progresses, representing an opportunity to visually present complex information to drivers, construction workers, agency personnel, and the general public.</p> <p>The purpose of this study is to continue the work from the previous study to determine the added value and resource demands created by including more complex data, specifically traffic volume, movement, and vehicle type. This report describes the changes that were made to the simulation, including incorporating additional data and converting the simulation from a desktop application to a web application.</p>		

APPLICATION OF VISUALIZATION AND SIMULATION PROGRAM TO IMPROVE WORK ZONE SAFETY AND MOBILITY

**Final Report
January 2010**

Principal Investigator

Kelly Strong
Associate Professor
Civil, Construction, and Environmental Engineering, Iowa State University

Co-Principal Investigators

Ed Jaselskis
Professor

Charles Jahren

Associate Professor
Civil, Construction, and Environmental Engineering, Iowa State University

Research Assistant

Manop Kaewmoracharoen

Authors

Kelly Strong and Manop Kaewmoracharoen

Sponsored by
the Smart Work Zone Deployment Initiative
and
the Iowa Department of Transportation

A report from

Institute for Transportation

Iowa State University

2711 South Loop Drive, Suite 4700

Ames, IA 50010-8664

Phone: 515-294-8103

Fax: 515-294-0467

www.intrans.iastate.edu

TABLE OF CONTENTS

ACKNOWLEDGMENTS	IX
1. INTRODUCTION	1
2. LITERATURE REVIEW	2
3. ANALYZE AND INTEGRATE INFORMATION.....	3
4. CREATE ENHANCED VISUALIZATION FROM INTEGRATED MODEL	4
4.1 Background and Improvement.....	4
4.2 Development	6
4.3 Data Requirements.....	10
4.4 Limitations	10
4.5 Recommendations.....	10
5. REFERENCES	12
APPENDIX A. MINIMUM SYSTEM REQUIREMENT FOR VIEWING SIMULATION	A-1

LIST OF FIGURES

Figure 1. Previous work zone visualization displaying different snapshots of a project from start to finish from the same perspective	4
Figure 2. Previous work zone visualization displaying different snapshots of a project at Stage 5 from different perspectives	4
Figure 3. Previous framework (left) and current framework (right).....	5
Figure 4. Diagram of simulation workflow using PHP generating KML files (left) and diagram of simulation workflow using JavaScript and DOM (right)	8
Figure 5. Traffic simulation with traffic volume displaying in a web browser	9

ACKNOWLEDGMENTS

The research team would like to thank the Iowa Department of Transportation, the Federal Highway Administration, the Smart Work Zone Deployment Initiative, and the Institute for Transportation at Iowa State University for their support of this research.

The research team also thanks the following members of the Technical Advisory Committee for their review, advice, and encouragement on this project:

- Mark Bortle Iowa Department of Transportation
- Troy Jerman Iowa Department of Transportation
- LaDon Jones Department of Civil, Construction, and Environmental
Engineering at Iowa State University
- Jeff Koudelka Iowa Plains Signing, Inc.
- Tom McDonald Safety Circuit Rider, Institute for Transportation
- Jerry Roche Federal Highway Administration, Iowa Division
- Willy Sorenson Iowa Department of Transportation
- Dan Sprengeler Iowa Department of Transportation

1. INTRODUCTION

A 2007/2008 study sponsored by the Smart Work Zone Deployment Initiative (Strong and Kaewmorachan 2008) demonstrated the feasibility of combining readily available, inexpensive software programs, such as SketchUp and Google Earth, with standard two-dimensional civil engineering design programs, such as MicroStation, to create animations of construction work zones. The animations reflect changes in work zone configurations as the project progresses, representing an opportunity to visually present complex information to drivers, construction workers, agency personnel, and the general public. One of the main findings of the previous study was the potential to incorporate additional modeling inputs to enhance the animations to include conditions under different traffic volumes, weather conditions, and construction operations. The purpose of this study is to continue the work of the initial visualization project to determine the added value and resource demands created by including more complex data, specifically traffic volume, movement, and vehicle type.

2. LITERATURE REVIEW

Koo and Fischer (2000) classified functions of 4D CAD systems into three categories: (1) visualization, (2) integration, and (3) analysis. Other researchers (Collier et al. 1996; Riley 2000; Webb et al. 2004; Williams 1996) also showed that the technology can significantly improve communicating the construction plan to other project stakeholders by simulating the construction process. McKinney et al. (1996) classified 4D CAD technology into two distinctive generations: Visual 4D CAD and Collaborative 4D CAD. Visual 4D CAD produces a 4D animation for designers to evaluate and review the designs they propose. While using 4D CAD to visualize can effectively communicate completed construction plans, it does not address how the schedule was developed because it merely links the 3D model with an existing schedule. Because of this, the researchers proposed “Collaborative 4D CAD” as a tool to improve the construction design process. Collaborative 4D CAD provides more of a simulation rather than a mere visualization of the construction process. Researchers have proposed several prototypes of simulation-based construction planning tools (Whyte et al. 2000; Waly et al. 2003; Xu et al. 2003; Clayton et al. 2002; Li et al. 2003; Chau et al. 2004).

Researchers have addressed a number of specific construction challenges to improve 4D CAD as a construction planning tool. Akinci et al. (1997) conducted productivity and cost analysis using 4D modeling. Riley (2000) studied the role of 4D modeling in trade sequencing and production planning. O’Brien (2000) proposed 5D CAD modeling by expanding 4D CAD models to include multi-project resource management functions for specialist contractors. Li et al. (2003) studied the application of virtual reality technology to experiment with innovative construction operations. Chau et al. (2004) used 4D CAD technology to address building construction site utilization issues. In addition to construction planning, 4D CAD and virtual reality also proved to be very effective education tools for architectural and construction engineering majors (Jaafari et al. 2001; Clayton et al. 2002).

The evidence from previous studies is clear: the benefits of visualization and simulation are significant. The research program described below outlines a low-cost visualization and simulation program that incorporates traffic modeling data in a transportation construction work zone for the 24th Street Bridge project in Council Bluffs, Iowa.

3. ANALYZE AND INTEGRATE INFORMATION

In the initial visualization study, the authors determined that the work zone visualization and simulation program could yield more benefits and expanded usage if the underlying animation models included traffic microsimulation. Designers and engineers could visualize how work zone settings affect traffic mobility as well as emphasize traffic safety. The previous study developed animations of construction work zones using a library of 3D object models, including construction equipment, traffic signs, and traffic devices. The initial animation displayed a sequenced set of simulations that users could play back as a time-linked animation in order to better understand work zone phasing and transitions during a defined, short period of time. However, the study did not show how traffic flow changes impacted different work zone setups. In the current follow-up study, traffic data were modeled and added to the existing animation program to create a visual representation of traffic patterns through the construction work zone. A set of traffic data (volume and movement) in the area of the construction work zone has been used to calculate an estimated traffic flow through the work zone.

The Iowa Department of Transportation (Iowa DOT) provided two sets of 2004 traffic data from Station no. 78 11 7968 1991 and Station no. 78 11 7698 5991 at the intersection of I-29/I-80 and South 24 Street in Council Bluffs, Pottawatomie County, Iowa. The data included vehicular turning movements, annual average daily traffic, and average traffic peak volumes during day times. The numbers of turning movements were summarized by separating right turn (RT), straight (ST), and left turn (LT) vehicles for each leg from north, east, south, and west. The traffic data were separated into one-hour segments from 7 a.m. to 6 p.m. (except for 10–11 a.m. and 1–2 p.m.). The numbers were also divided by vehicle types, using the categories of passenger car, single-unit trucks, and combination trucks. All traffic data were reorganized into a new format to facilitate incorporation into an animation programming file, as discussed in the following sections.

4. CREATE ENHANCED VISUALIZATION FROM INTEGRATED MODEL

4.1 Background and Improvement

The animation developed in the initial study shows a 4D simulation that displays work zones using 3D models during different time periods. Users can easily see different work zone configurations by placing the time navigation bar on a specific time period, as displayed in Figure 1. The 3D model is beneficial for displaying a similar set of data in a single visualization window. All of the 3D models can be linked to allow the program to run as an animation to show how the work zone transitions from one phase to another phase, emphasizing what aspects remain the same or change between each phase. The primary benefit of the 4D animation is that it eliminates the tedious job of flipping back and forth on traffic control plans to identify what aspects are the same or different from several sheets of construction drawings. Another benefit of the full 4D model, as displayed in Figure 2, is that it is able to display different perspectives of the same models. The models can be controlled in three-dimensional navigation, which allows users to freely zoom and rotate within the graphic model. Users can see every view in real time, unlike with 3D animations, which typically allow users to view select sides of models provided by the animation creators. The users can perceive the full benefit of three-dimensional data, such as overlapping or interfering objects.

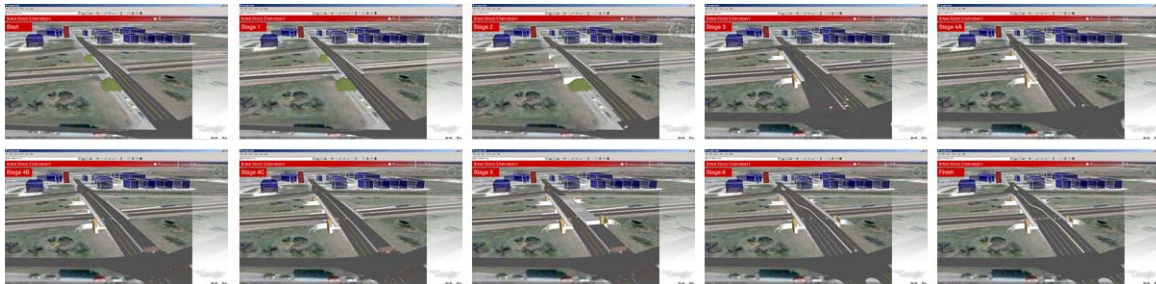


Figure 1. Previous work zone visualization displaying different snapshots of a project from start to finish from the same perspective

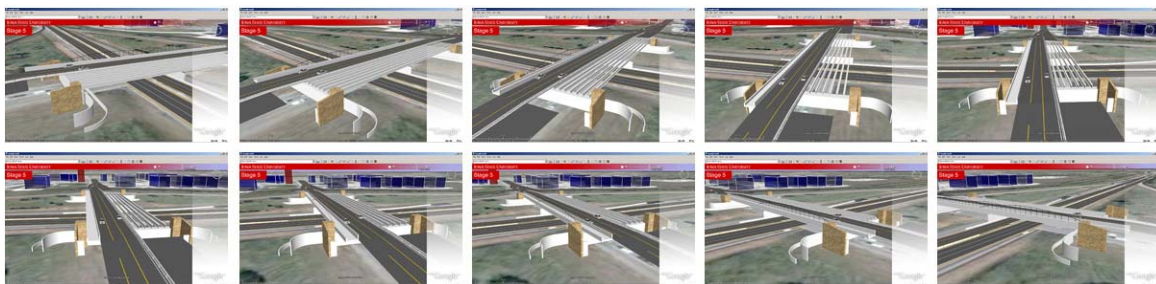


Figure 2. Previous work zone visualization displaying different snapshots of a project at Stage 5 from different perspectives

For the software side, the main benefit of this visualization and simulation is the use of an open platform software program. This feature means that all data files are saved and kept in open formats that should be available to anyone without the need for expensive proprietary software,

making the visualization and simulation program an inexpensive alternative with the possibility of further developments. In this animation, a combination of standard software packages were utilized, including JavaScript (coding), KML (markup language), and DAE (3D model). All of these are standards supported by several large companies, such as Google and Mozilla.

One major drawback of the previous study was that the animation program required users to have Google Earth installed. To make the simulation more accessible, it was rebuilt to be available via a web browser. Several codes were rewritten and ported as a web application. The original animation is currently hosted at <http://itshee.com/traffic>.

4.1.1 Enhancement as a Web Platform

Since the Internet is rapidly becoming a universally available infrastructure, the research team transformed the previous simulation from a desktop application to a web application. The basic technology, or the web platform, has been available since 2008 when Google announced the support of Earth API. The research team started transforming the same geospatial data set that previously worked only on the Google Earth framework to a web framework. The same data created from SketchUp and KML were used as another layer of data sets on top of Earth API and JavaScript instead of Google Earth, as illustrated in Figure 3. The web platform allows everyone to run the simulation via a standard web browser, including Chrome, Firefox, Internet Explorer, and Safari.

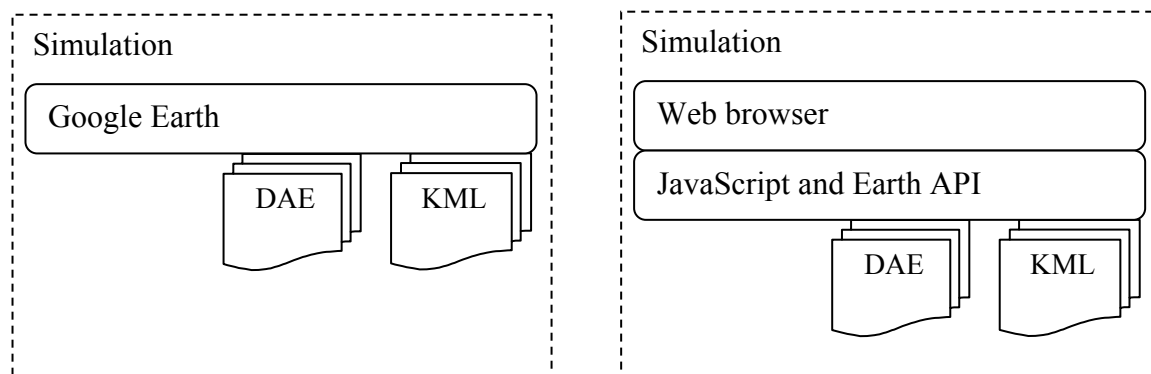


Figure 3. Previous framework (left) and current framework (right)

Moving the animation program from a desktop application to a web application made it possible to use a cloud computing technique, which allows users to create, modify, and adapt their own simulations. After transforming the initial animation into a new web application, the research team enhanced the animation by incorporating a traffic microsimulation, adding vehicle volume and movement data into the existing simulation program.

The visualization program from Phase I, enhanced as a web application, is available for viewing at <http://itshee.com/traffic/phase1/>.

4.1.2 Enhancement with Traffic Microsimulation

Traffic microsimulation was added to the original work zone simulation program to increase the value and benefits of the system. Currently, there are several traffic microsimulation software packages that range from high-end software like CityScape® from PixelActive (\$19,000) to research software like MicroSim from the Dresden University of Technology (available for free for use on research projects). Each software package comes with different features and usages at different prices. The research team studied several traffic simulation programs for possible incorporation into the work zone simulation program. The software programs examined included Aimsun, BABSIM, CityScape®, Cube Dynasim, Dynameq, FREQ, MicroSim, Paramics, SIDRA Intersection, Synchro plus SimTraffic, TransModeler, TSIS-CORSIM, and HCS.

MicroSim was deemed to be the most compatible existing traffic simulation program, with features and design purposes similar to the existing Google/SketchUp work zone simulation. However, the research team ultimately decided to create the traffic simulation from scratch instead of attempting to integrate a proprietary program. The custom traffic simulator used a basic construct similar to the object-oriented concepts found in MicroSim. This is consistent with the research objectives of both Phase I and Phase II of the visualization study, which were to develop low-cost, accessible animations using non-proprietary modeling programs, such as Google, Adobe SketchUp, etc.

4.2 Development

The methods used to incorporate traffic simulation into the existing animation program are explained in the following section. The primary goal was to deploy the existing work zone animation as a web application with included traffic microsimulation.

4.2.1 Technology Involved

All software used in this study fully supports open standards, which are listed below:

Keyhole Markup Language (KML)—a markup language first developed by Keyhole that was acquired and is now maintained by Google. It is a native language used in Google Earth software. The data file is saved in a simple text file format according to the XML (eXtensible Markup Language) schema. Each data element represents spatial information, which includes object locations such as latitude and longitude. The KML file can be compressed as KMZ (KML zip format) for easy transfer over a network.

COLLADA (.dae)—an open format for 3D models. The data file is also a text file formatted in XML schema. In this study, SketchUp was used to create 3D model COLLADA files.

PHP—a server-side programming language. It was used for calculating several iterations of algorithms used in the traffic simulation.

JavaScript—a script language that is heavily used for interactive design. It is a major component in modern web browsers. In this study, it works with Earth API to interact with 3D digital globes similar to those in Google Earth. The primary function of JavaScript programming is to load the KML file into a 3D application.

Earth API—a plug-in that allows the user to interact with information from the Google Earth server via a web browser without installing Google Earth software. It interacts with JavaScript to allow users to manipulate data in 3D applications over a digital globe.

4.2.2 Workflow

The enhanced simulation program is composed of 3D work zone models and traffic microsimulation. These two major components are created separately. The 3D models were created in Phase I of this study using SketchUp based on 2D plans of design drawings. Once completed, they were saved in a COLLADA format (.dae) to be available to work with other software in KML and JavaScript. The research team created 3D models based on the 24th Street Bridge renovation project in Council Bluffs, Iowa. Details of Phase I model creation are explained in the final report of the initial visualization study (Kaewmoroachan and Strong 2008). The second part of the animation, introduced in this study, is traffic simulation. It defines traffic volumes and movement behaviors within the simulation program.

The traffic microsimulation was programmed in KML. Each line of KML code describes objects (e.g., structure, vehicle) and spatial data (i.e., latitude and longitude) to display 3D models compiled via Earth API and JavaScript. Early in the study, the research team attempted to use PHP programming to generate KML files. However, after several tests of the animation, PHP was dropped due to performance problems. Specifically, when there are large traffic volumes, file sizes become very large, causing the simulation program to play back animation in slow and choppy sequences and sometimes even freezing the playback. The workflow was slightly changed by adopting Document Object Model (DOM) to use with JavaScript. This approach created KML objects in computer memory instead of KML files without the need to transfer a large file over the network. The diagrams in Figure 4 display the two different approaches used in this project.

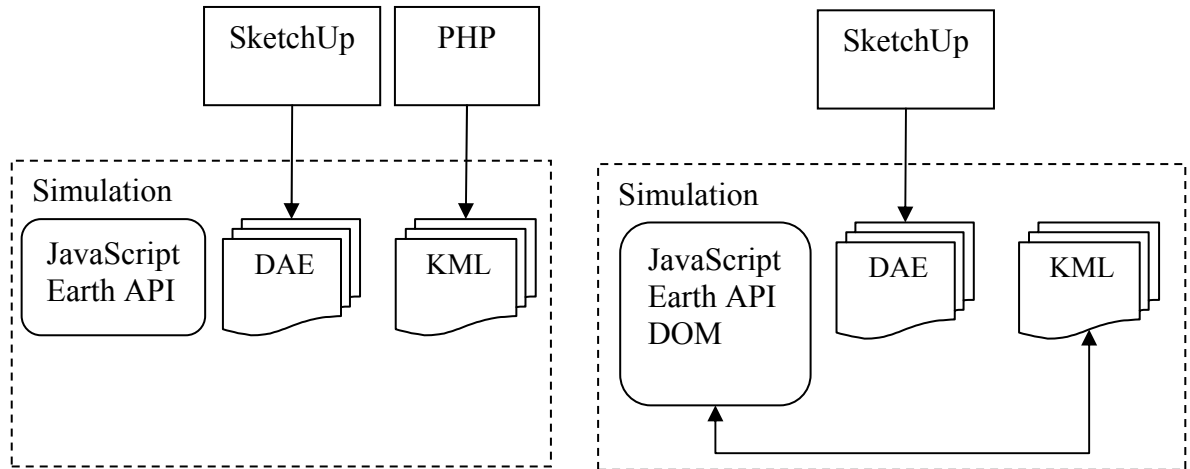


Figure 4. Diagram of simulation workflow using PHP generating KML files (left) and diagram of simulation workflow using JavaScript and DOM (right)

The traffic movements start when DAE and KML files are loaded into the simulation via JavaScript and Earth API. The road and vehicle type generated are assigned specific properties and behaviors similar to real-world objects. Several preset values, including location, latitude, longitude, altitude, and length, are assigned to each simulated road according to real information. Traffic variables from the Iowa DOT such as traffic volumes (average and peak), percentages of trucks, and percentages of direction turns are also assigned to each road. Then, the computer-generated vehicles are calculated from those values.

After the simulation program starts, all of the vehicle's properties will retrieve new values, such as a new location and/or speed according to their settings and locations. Based on programmed algorithms, some vehicles will increase or decrease their velocities if their conditions are met. A vehicle will be assigned to a road according to the traffic data. If the vehicle moves close to a road junction, it will "check" the traffic light object within the model to determine if the vehicle is allowed to continue or needs to wait at the road junction. If the following vehicles move close to the vehicle in front of them, they will reduce speed to prevent hitting the front vehicles. Within the model, vehicles accelerate and decelerate automatically based on distance from the front vehicles. Every vehicle will have similar behaviors according to road information and time of day. The clock in the Phase II simulation program starts at 7 a.m. and runs until 6 p.m. However, the traffic modeling clock does not necessarily reflect the real-time clock for performance purposes. In addition to the file size limitations created by traffic volumes, setting time increments to very small, discrete values (e.g., 5 minutes) also creates very large file sizes. Unlike the construction schedule data included in Phase I, which could be programmed in discrete time segments of days or weeks, traffic movement is more of a continuous event. This presents technical challenges when attempting to program using discrete time elements with a goal of keeping file sizes small enough to maintain web-based accessibility for a large number of users.

Several other traffic microsimulation conditions and assumptions are listed below:

- The vehicles in the microsimulation will change velocity and acceleration according to distance between a vehicle in front compared to the object vehicle itself.
- The vehicles will slow down if the distance to the vehicle in front is less than the safe distance to stop the vehicle.
- The vehicles will speed up if there is a large distance in front of the vehicle itself until the velocity reaches the posted speed limit for the work zone.
- Traffic volume and turning behaviors used in this study are based on traffic data from the Iowa DOT of the 24th Street and Interstate 80 traffic (without construction work zones) in the year 2004.
- There are three vehicles types in the simulation: cars, single-unit trucks, and combination trucks. The number of each vehicle type was calculated from the traffic data.
- The simulation vehicles will not change lanes in the simulation program. Within the animation, there is sufficient space for additional vehicles in an adjacent lane while depicting a traffic jam in front. However, the inclusion of lane changing behaviors requires a more complex traffic algorithm than could be accommodated in this phase of the study.
- The simulation clock does not reflect the real-world clock. One second of the traffic clock is about 30 seconds in real time due to performance issues and limitations of the software.

A screenshot of the traffic simulation is displayed in Figure 5, which shows a work zone with traffic volume.

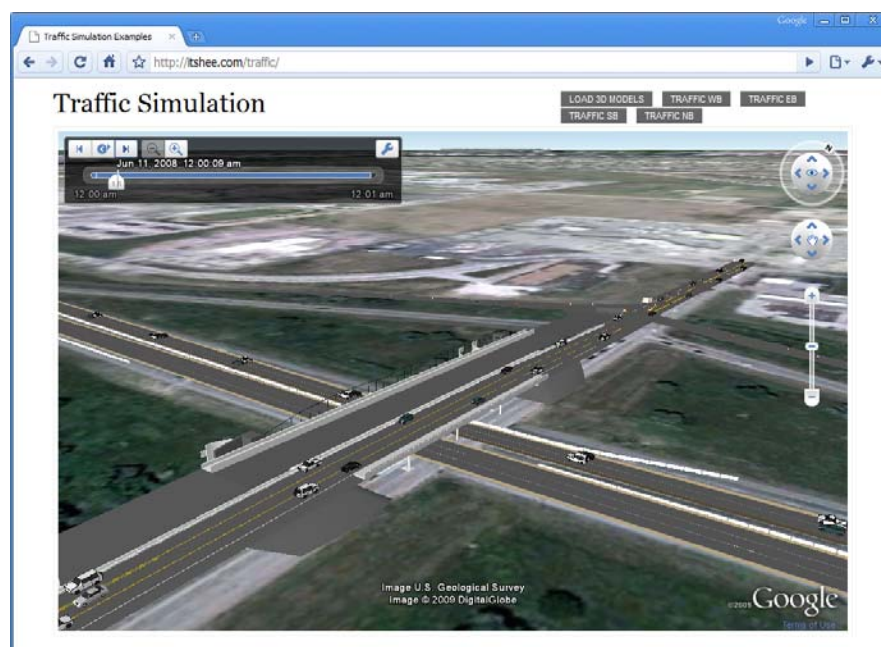


Figure 5. Traffic simulation with traffic volume displaying in a web browser

The Phase II visualization program with traffic microsimulation is available for viewing at <http://itshee.com/traffic>.

4.3 Data Requirements

To create a traffic simulation for urban reconstruction projects, specific information sets are required. The information used to generate microsimulation and work zone models is as follows:

- Work zone information—locations, structure details, work zone signs and devices, road closures, traffic directions, detour information (if available)
- Traffic information—traffic volume (average and peak), movement, vehicle mix, speed limits

Development time and costs will be mostly in development of 3D models, as explained in detail in the final report of the initial simulation development (Kaemorocharoen and Strong 2008). The same coding can be reused and adopted into other projects, unless more complex algorithms and conditions of traffic movements are needed. Users are not required to purchase special software. Some required software may be downloaded for free from websites such as Earth API (<http://code.google.com/apis/earth/>). Minimum system and hardware requirements used to view the simulation are listed in Appendix A.

4.4 Limitations

The Phase I study worked only on Google Earth software, but the results of this study show that a simplified traffic simulation works as a web application running on a basic web browser. However, with the current technology, it is still limited to a desktop application on Windows or Mac OS X. The enhanced simulation cannot work on a web browser on any mobile devices; however, there are ongoing improvements aimed at using Google Earth in some mobile devices, such as iPhone OS and Android OS. Performance issues are also a major concern in the enhanced simulation program. In a simulation with large traffic volumes, complex traffic movements across short, discrete time intervals, and multi-lane work zones, the simulation program rapidly loses performance capabilities, becoming slow, choppy, and non-responsive or freezing completely.

4.5 Recommendations

In the enhanced simulation, there is still room for improvements in incorporating traffic data. More complex algorithms of traffic movement can be developed, but performance problems caused by file size impose limitations on the feasibility of such complexity. As open platform software and information processing technology advances, the traffic microsimulation can incorporate more complex behaviors, such as lane changing or on-ramp merging. However, until more advanced technologies are developed, current applications should be limited to work zones with relatively low traffic volumes, single-lane traffic (no lane changing capabilities), and few

turning options over relatively large time intervals (i.e., turns only at timed, signalized intersections as opposed to grade-separation interchanges with “continuous” turning movement).

5. REFERENCES

- Akinci, B., Staub, S., and Fischer, M. (2005). Productivity and cost analysis based on a 4d model, Construction Informatics Digital Library, <http://itc.scix.net/data/works/robots/w78-1997-23.htm>, last visited: Feb 13, 2005.
- Chau, K. W., Anson, M., and Zhang, J. P. (2004). Four-dimensional visualization of construction scheduling and site utilization, *Journal of Construction Engineering and Management*, Vol. 130, No. 4, p. 598.
- Clayton, M. J., Warden, R. B., and Parker, T. W. (2002). Virtual construction of architecture using 3D CAD and simulation, *Automation in Construction* 11, pp. 227–235.
- Collier, E. and Fischer, M. (1996). “Visual-based 4D modeling on the San Mateo County Health Center.” *Proceedings of the Third Congress on Computing in Civil Engineering*, Jorge Vanegas and Paul Chinowsky (Eds.), ASCE, Anaheim, CA, June 17-19, 1996, pp. 800–805.
- Jaafari, A., Manivong, K. K., and Chaaya M. (2001). VIRCON: Interactive system for teaching construction management, *Journal of Construction Engineering and Management*, Vol. 127, No. 1, p. 66.
- Kaewmoroachan, M. and Strong, K. (2008). “Utilizing Open-Format Visualization Programs to Improve Work Zone Safety and Mobility” *Proceedings of the First International Transportation Construction Management Conference*, Orlando, FL.
- Koo, B. and Fischer, M. (2000) Feasibility study of 4D CAD in commercial construction, *Journal of Construction Engineering and Management*, Vol. 126, No. 4, p. 251.
- Li, H., Ma, Z., Shen, Q., and Kong, S. (2003). Virtual experiment of innovative construction operations, *Automation in Construction* 12, pp. 561–575.
- McKinney, K., Kim, J., Fischer, M., and Howard C. (1996). “Interactive 4D CAD.” *Proceedings of the Third Congress on Computing in Civil Engineering*, pp. 383–389.
- O’Brien, W. (2000). Towards 5D CAD – Dynamic Cost and Resource Planning for Specialist Contractors. *Proceedings of the Sixth Construction Congress*, pp. 1023–1028.
- Riley, D. (2000) The role of 4D Modeling in Trade Sequencing and Production Planning. *Proceedings of the Sixth Construction Congress*, pp. 1029–1033.
- Strong K. and Kaewmorachoen, M. (2008) Feasibility of visualization and simulation applications to improve work zone safety and mobility, *Final Report - Smart Work Zone Deployment Initiative*.
- Waly, A. F. and Thabet, W. Y. (2003). A Virtual Construction Environment for preconstruction planning, *Automation in Construction*, Vol. 12, No. 2, pp. 139–154.
- Webb, R. M., Smallwood, J., and Haupt T. C. (2004). The potential of 4D CAD as a tool for construction management, *Journal of Construction Research*, Vol. 5, No. 1 p. 43–60.
- Whyte J., Bouchlaghem N., Thorpe A., and McCaffer R. (2000). From CAD to virtual reality: modeling approaches, data exchange and interactive 3D building design tools, *Automation in Construction* 10, pp. 43–55.
- Williams, M. (1996). Graphical simulation for project planning: 4D-Planner™ *Congress on Computing in Civil Engineering, Proceedings*, pp. 404–409.
- Xu, J., AbouRizk, S.M., and Fraser, C. (2003). Integrated three-dimensional computer aided design and discrete-event simulation models, *Canadian Journal of Civil Engineering*, 30: 449–459.

APPENDIX A. MINIMUM SYSTEM REQUIREMENT FOR VIEWING SIMULATION

Microsoft Windows System

- Operating System: Windows 2000, Windows XP, or Windows Vista
- CPU: Pentium 3, 500Mhz
- System Memory (RAM): 256MB
- Hard Disk: 400MB free space
- Network Speed: 128 Kbits/sec
- Graphics Card: 3D-capable with 16MB of VRAM
- Screen: 1024x768, "16-bit High Color" - DirectX 9 (to run in Direct X mode)
- Web Browsers: Chrome, Firefox, Flock, or Internet Explorer
- Software: Google Earth plug-in

Apple Mac OS X System

- Operating System: Mac OS X 10.4.0
- CPU: 1 GHz
- System Memory (RAM): 256MB
- Hard Disk: 400MB free space
- Network Speed: 128 Kbits/sec
- Graphics Card: 3D-capable with 16MB of VRAM
- Screen: 1024x768, "Thousands of Colors"
- Web Browsers: Firefox or Safari
- Software: Google Earth plug-in