A Global System for Transportation Simulation and Visualization in Emergency Evacuation Scenarios

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ABSTRACT
Simulation-based studies are frequently used for evacuation planning and decision making processes. Given the transportation systems complexity and data availability, most evacuation simulation models focus on certain geographic areas. With routine improvement of OpenStreetMap road networks and LandScan^{TM} global population distribution data, we present WWEE, a uniform system for world-wide emergency evacuation simulations. WWEE uses unified data structure for simulation inputs. It also integrates a super-node trip distribution model as the default simulation parameter to improve the system computational performance. Two levels of visualization tools are implemented for evacuation performance analysis, including link-based macroscopic visualization and vehicle-based microscopic visualization. For left-hand and right-hand traffic patterns in different countries, the authors propose a mirror technique to experiment with both scenarios without significantly changing traffic simulation models. Ten cities in US, Europe, Middle East, and Asia are modeled for demonstration. With default traffic simulation models for fast and easy-to-use evacuation estimation and visualization, WWEE also retains the capability of interactive operation for users to adopt customized traffic simulation models. For the first time, WWEE provides a unified platform for global evacuation researchers to estimate and visualize the performance of transportation systems under evacuation scenarios.

Keywords
Evacuation Visualization, Large-Scale Evacuation, Spatiotemporal Visualization, High-Resolution Data, Traffic Simulation and Visualization

1. INTRODUCTION

Natural or man-made disasters, such as hurricanes and hazard material leaks, have tremendous impacts on urban transportation systems. It is critical for emergency managers and transportation professionals to have an efficient evacuation plan during these kinds of infrastructure interruptions. Simulation-based studies are commonly used in evacuation planning and decision making processes. Most existing simulation models in transportation evacuation are restricted to certain geographic areas and selected traffic simulation tools. Each tool has its own data format requirement and simulation preferences (macroscopic, mesocopic, or microscopic). Also, the visualization work in transportation evacuation is limited and not scalable. These lead to the need for a uniform simulation tool in the evacuation planning community, so that researchers can focus on improving traffic models in travel demand, trip distribution, and traffic assignment areas with more directly visual analysis.

This motivated the authors to develop an easy to use global system, WWEE (World-Wide Emergency Evacuation), for emergency evacuation simulations that are applicable to any geospatial locations in the world. WWEE integrates the weekly updated OpenStreetMap road networks data and annually updated LandScan™ global population distribution data as the major data resources [1, 2]. Given the transportation systems complexity and data availability, the authors implemented some general traffic simulation models as default parameters. To improve the system computational performance, we also proposed a super node trip distribution algorithm for quickly generating evacuation O-D matrix. WWEE can simulate both right-hand and left-hand traffic with the same traffic simulation models. Scalable microscopic and macroscopic visualization tools are integrated for visual analysis and performance estimation. The authors demonstrated ten evacuation case studies (including Alexandria, Fort Belvoir, Knox County, Washington D.C., Seattle, Beijing, Berlin, Doha, Singapore, and Taipei) to prove the system concept.

The major contributions of WWEE are:

- **Unified data structure:** Utilizing OpenStreetMap and LandScan™ as unified input data structure for any geospatial locations and generating the same output data format for performance analysis and visualization.
- **Super node trip distribution algorithm:** Proposing a trip distribution model for fast O-D matrix generation by connecting a super node as a dummy destination to all possible safe shelters.
- **Left-hand traffic supported:** Extending the existing traffic simulation models to handle both right-hand traffic and left-hand traffic through mirror technique (flip the x coordinates) without changing the traffic models for a demonstration.
- **Two levels of visualization:** Implementing macroscopic level visualization for link-based network performance analysis and microscopic level visualization for vehicle-based driving behavior monitoring.

2. LITERATURE REVIEW

Simulation-based evacuation studies are widely used for emergency management and strategy planning. Some tools are specially developed for evacuation simulation studies. A few examples are NETVAC1, OREMS, MASSVAC, I-DYNEV, EVAQ [3-7], and others. This kind of tools provided good facilities for evacuation simulation studies at an early stage. More recently, traffic simulation tools used for regular day-to-day traffic applications have been adapted in evacuation simulation areas. These include DYNASMART , DynusT , PARAMICS, MITSIM , TRANSIMS, MATSim [8-14], among others. Most of these tools have their own input and output data formats and requirements. This causes transportation researchers and emergency managers to spend more time on data preparation, especially in large-scale evacuation studies with high-resolution data. Also, most outputs need traffic engineering knowledge for data processing and analysis. Transportation professionals in evacuation management areas who are not engineers will appreciate direct visualization of simulation results.

Development of big data analysis and visualization in transportation systems has brought tremendous challenges and opportunities to the transportation research community. Traditionally, visualization in transportation focused on context-sensitive design with computer image generation and rapid database development [15]. Shekhar et al. proposed a CubeView system for visualizing transportation data from Minnesota Department of Transportation [16]. It integrated road maps and five-minute interval detectors data to plot the traffic volume and occupancy in selected areas. Wang developed a prototype system to display GIS maps and simulation results for traffic impact analysis [17]. This system emphasizes the ability to visualize environmental impacts from transportation systems. Pack et al. produced a four-dimensional interactive transportation visualization tool to visualize real-time transportation data from Washington D.C., Maryland, and Northern Virginia.[18] They integrated GIS and transportation infrastructure data in conjunction with real-time traffic management center data. Most of these visualization tools are developed for regular day-to-day traffic operation management, although some claims capability for emergency management purposes.

The use of visualization in transportation system resilience and evacuation performance is a new development. Zobel stated a disaster resilience triangle concept for illustrating the relationship between the initial impact of a disaster event and the subsequent time to recovery [19]. This method visualizes resilience performance from a planning perspective with resilience curves. Researchers at the VMASC lab at Old Dominion University developed a web-based evacuation planning tool for the United States, and provided a Traffic Analysis Zones (TAZ) based macroscopic visualization to demonstrate evacuation performances [20]. The computer graphics community can help transportation professionals to understand our transportation systems in a clear and efficient manner [21]. The advanced information technologies can help us to build a global system for emergency evacuation studies with simplified data preparation and effective visualization.

3. THE WWEE SYSTEM

Figure 1 described the system architecture of WWEE. Three main components are included: data processing, traffic simulation models, and web-based visualization.

3.1 Data Processing

The data processing procedure has three major tasks: 1. Defines evacuation shelters; 2. Prepares input data for traffic modeling and simulation; 3. Implements user-defined evacuation strategies. By default, shelters are defined as the intersection of road links and evacuation area boundary without considering the capacity limit. In another word, vehicles arrive at shelters when they reach the boundary. Users can define shelters' location and capacity information with local detailed data. LandScan population data and OpenStreetMap road network data are subtracted and converted for the input data preparation. If users have any specific evacuation strategies, the input data can be prepared depending on requirements. For example, users can reverse the link direction to implement contra-flow control for evacuation. Also, users can assign the zone types as a new attribute for LandScan data to implement staged evacuation orders. After cleaning up and processing these data, the system produced unified data structures of road network and traveler information for traffic simulation in evacuation scenarios.

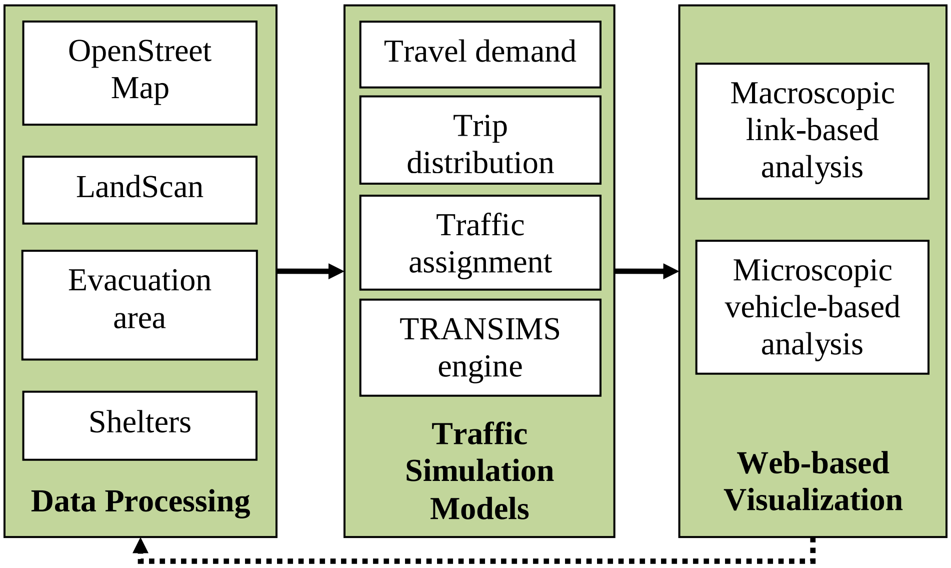


FIGURE 1 The WWEE System Architecture.

Users can define an evacuation area with circular or administrative boundaries. Figure 2 shows the road network data for an evacuation case study in Alexandria, Virginia. The road network from OpenStreetMap is processed and displayed in colors based on the road types. LandScan provides daytime and nighttime datasets, as shown in Figure 3. The LandScan population data (in raster format) is represented by colored rectangles from red to yellow (red means higher population, and yellow means lower population).

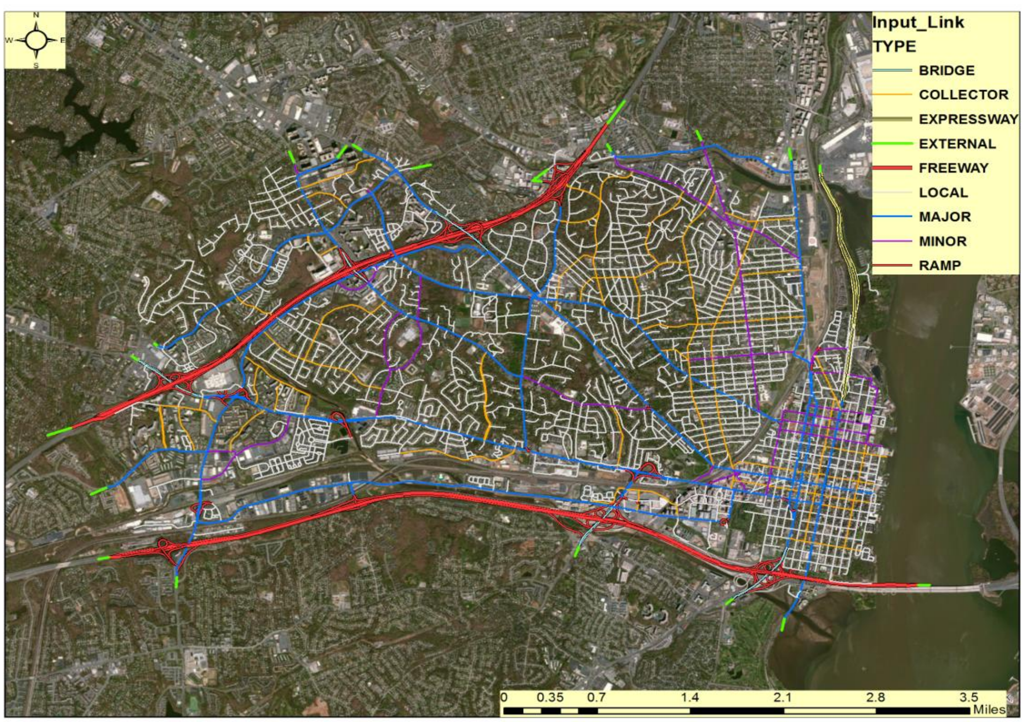
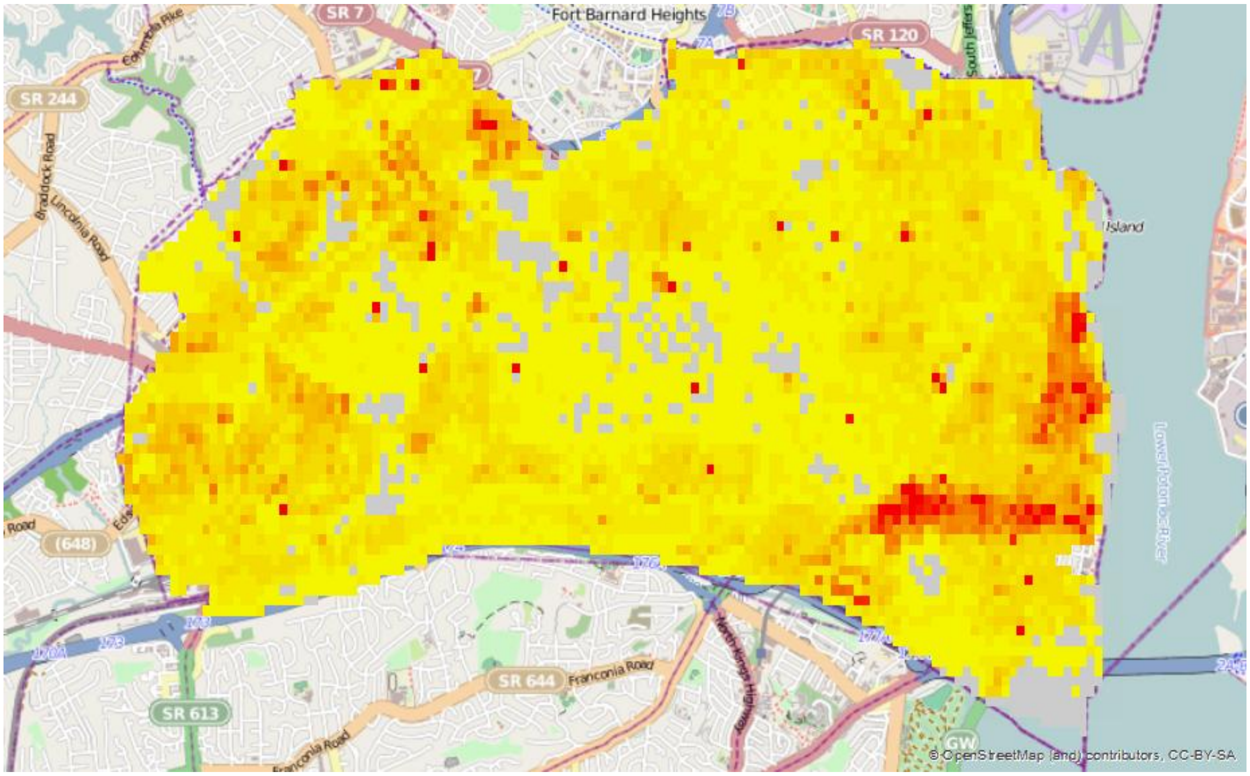
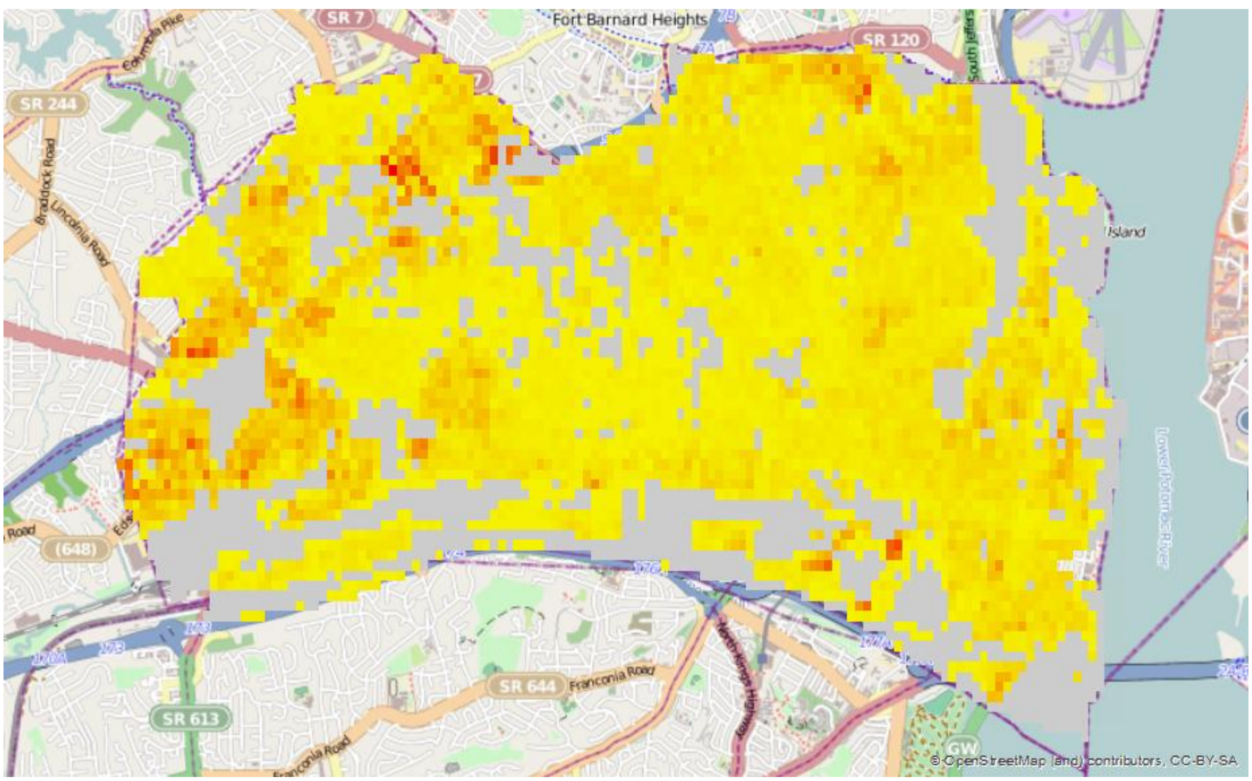


FIGURE 2 Alexandria city streets network based on road types.



(a)



(b)

FIGURE 3 Alexandria city LandScan population data cells: (a) Daytime (b) Nighttime; red means higher population; yellow means lower population; grey means no value.

3.2 Traffic Simulation Models

Traffic simulation models are conducted to answer two major questions in evacuation scenarios: 1. How to predict travelers' decisions through simulation? 2. How accurate are simulation results for planning evacuation strategies?

The first question is related to the choice to evacuate, departure time choice, destination choice, and route choice. This can be interpreted by modeling travel demand, trip distribution, and traffic assignment [22]. The second question can be answered through effective analysis and visualization of simulation results.

3.2.1 Travel demand modeling

Travel demand models generate the number of people in an evacuation, and the departure times. Survey-based studies are widely used in travel demand modeling. The WWEE implemented some often used models in WWEE and retained the ability to adapt user customized model. The authors used the vehicles-per-capita value to calculate the number of trips for each LandScan Population Cells (LPC). For example, if the population number in a certain LPC is 100 and the vehicles-per-capita ratio is 0.8, the number of trips in this LPC is 80 by default. Users can customize this value for each cell based on local land use and demographic information. For the departure time choice models, S-shape loading curves are most accepted in empirical studies [23]. The Weibull distribution is set as the default model in WWEE, which is given by

$$D(t) = 1 - \exp\left(-\beta t^{\gamma}\right) \tag{1}$$

Where $D(t)$ is the cumulative percentage of people who left at time *t*. The values of β and γ determine the shape of the distribution for faster or slower response to an evacuation order. Real evacuation scenarios vary depending on geographic locations and demographic information. The WWEE provides a template for departure time modeling with certain time interval, such as five minutes. Users can decide the percentage of trips assigned in each time slot among the whole simulation time based on their surveys. It also uses a program to smooth the distribution of trips in certain time slot to avoid the impulse-style trips input, where all the trips are assigned to the network at the very beginning of each time interval.

3.2.2 Trip distribution modeling

Trip distribution explains where people are willing to go for their safe destinations. In WWEE, it was assumed that travelers will choose the nearest shelters outside the evacuation area. The shelters are located at the evacuation area boundary and connected to the street links. The evacuees in each LPC cell choose the nearest destination in D based on travel time, where D is the number of destinations. The objective is to find the minimal initial travel time for people in each LPC cell. The implementation of normal Dijkstria's shortest path algorithm has to run S times shortest path algorithm to find the O-D pair for each source node and destination node, where S is the number of LPC cells. The time complexity is

$$\mathbf{O}(\mathrm{S} * (\mathrm{E} + \mathrm{V}) * \log \mathrm{V}) \tag{2}$$

Where E is the number of edges/links in the road network; V is the number of vertices/nodes in the network. If all the destinations are connected to a dummy super node and reverse the network structure (direction of links), as shown in Figure 4, only one time run of Dijkstria's algorithm can produce the same O-D matrix output. In another word, instead of searching the shortest paths from each source node to its nearest destination, the super node based algorithm connected all the destinations to a dummy destination with the same weight and search the shortest paths from destination to each source node. The time complexity for the proposed algorithm is

$$\mathbf{O}(((E + D) + (V + 1)) * \log(V + 1)) \quad (3)$$

This super node trip distribution algorithm was tested on different road network sizes, from a one-mile radius circle to a ten-mile radius circular area in a real world network. The ratio of the traditional Dijkstria's algorithm and the proposed super node algorithm's computational time increased exponentially (from 485 times in a one-mile radius area to 45,240 times in a ten-mile radius area) [24]. This saved a significant amount of computational time.

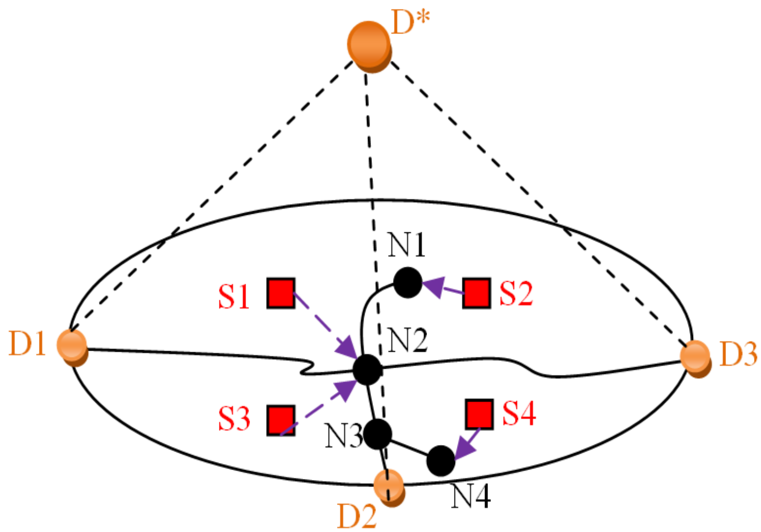


FIGURE 4. Demonstration of super node trip generation algorithm

3.2.3 Traffic assignment modeling

Traffic assignment determines how travelers get access to the road network and which routes they will choose to approach destinations. Most existing models use Traffic Analysis Zones (TAZ) as their zoning technique. WWEE uses LPC as zones to deploy activity-based simulation models. Figure 5 shows how LPCs are assigned to their nearest activity locations. The selected rectangular area is part of one TAZ zone, which is much larger than LPC cells. The black points are the central points of LPC cells. The blue points are activity locations, where vehicles access the road network. The red lines are major roads. The black lines are local roads. The short purple lines are lane connections. The green lines demonstrated how LPC cells connect with road network. All the trips in one LPC cell connect to the nearest activity location. This is more realistic because population density varies from one place to another place. In TAZ based method, trips in one big TAZ are evenly assigned to all the activity locations. This underestimates the travel time in the vehicle queue to access roads. The standard deviation of the number of trips in activity locations under TAZ is much lower than LPC, although their average value is almost the same.

To address the evacuation routing problem, the authors modified the dynamic traffic assignment module from the Transportation Analysis and Simulation Systems (TRANSIMS) package to fit LandScan zoning data structure. Traveler compliance in using selected routes is a practical concern for improving the model's accuracy [25]. This model also provides the option to set compliance levels for route choices from the destination perspective [26].

There is debate over the effectiveness of User Equilibrium (UE) in evacuation simulations [22]. UE is widely used in normal traffic assignment with good assumption that every traveler uses the shortest path as preferred route. For evacuation scenarios, travelers might consider other issues besides shortest travel time where UE does not exist. WWEE implemented two traffic assignment models with and without UE to give users this option to fit their own case studies.

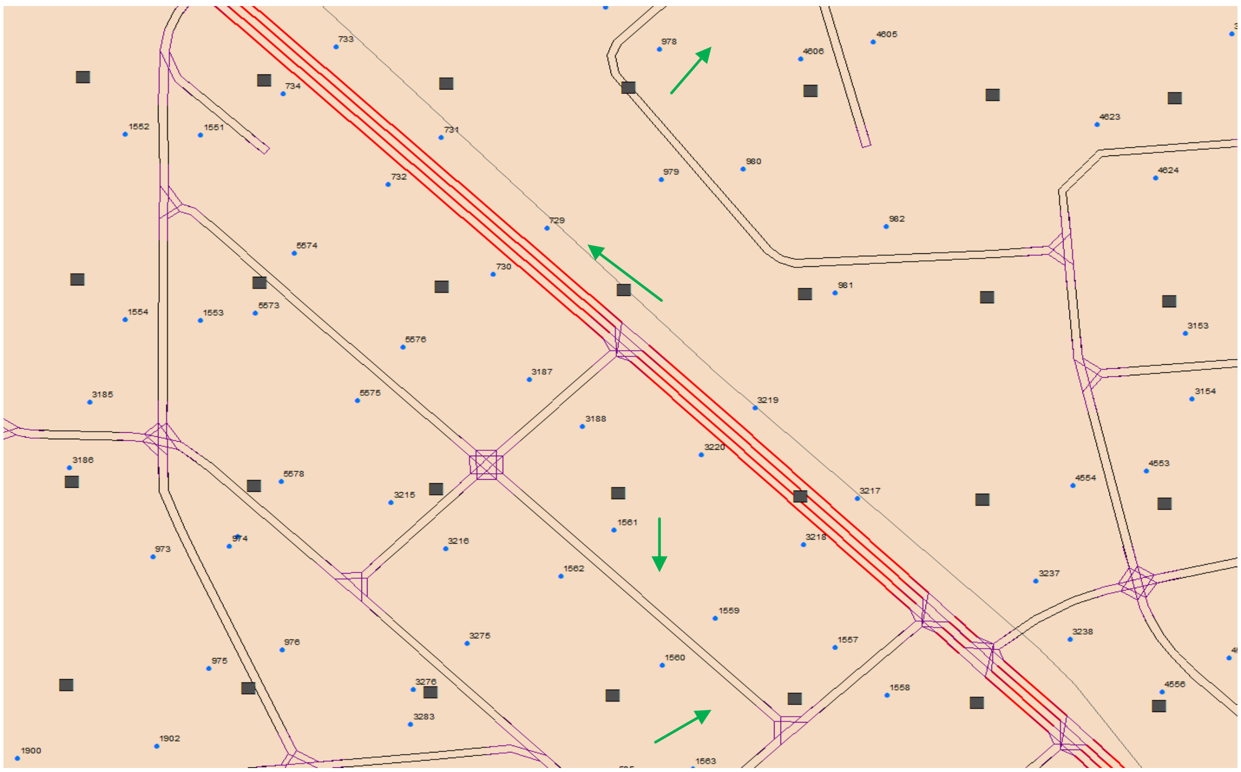


FIGURE 5 LPC based Activity-based Traffic Assignment.

3.2.4 TRANSIMS engine

Microscopic traffic simulations can provide more detailed analysis in evacuation studies. The authors modified the microscopic simulation module in TRANSIMS to provide the ability to handle the immense volume of LandScan cells and large-scale geospatial simulations. Next, the entire system was compiled in Ubuntu Linux, Windows 7, and Mac OS to maintain platform independence. The WWEE uses dynamic traffic assignment to generate the macroscopic traffic simulation results in TRANSIMS format. The microscopic traffic simulation in TRANSIMS uses cellular automata models to simulate how each vehicle agent makes decisions to move, stop, accelerate, or decelerate based on four rules, including acceleration, deceleration, randomization, and vehicle movement [27]. The simulation outputs are summarized in the same data format (15-minute interval output for link-based macroscopic simulation results and second-by-second trajectory output for vehicle-based microscopic simulation results) to provide uniform analysis and visualization.

3.3 Left-Hand Traffic Modeling

From a global perspective, there are 163 countries and territories that use right-hand traffic while 76 countries use left-hand traffic [28]. Most existing traffic simulation packages are designed for right-hand traffic simulation. Some simulation packages, such as VISSIM, provide the ability to define road regulations at limited scale. To handle large-scale traffic simulation with more than 10,000 links and one million population scenarios, it would be more efficient to use existing models without changing fundamental rules.

The traffic simulation models in WWEE use Universal Transverse Mercator (UTM) projection for road network data. The majority of the UTM system consists of 60 zones to cover 80°S and 84°N in World Geodetic System 1984 (WGS84), which is used by OpenStreetMap and LandScan datasets. The projection between WGS84 and UTM can be easily converted with a unique value for each point in both systems. Each UTM zone has the same ranges for x and y values in a two-dimensional Cartesian coordinate system. Also, all x values in one UTM zone are positive. The x value of the center in one UTM zone is 5,000,000. The equatorial radius is about 6,378,137 meters. In this case, the minimum and maximum x values can be calculated by

$$x_{min} = x_0 - \frac{radius}{2} = 5{,}000{,}000 - \frac{6{,}378{,}137}{2} = 1{,}810{,}931.5 \tag{4}$$

$$x_{max} = x_0 + \frac{radius}{2} = 5{,}000{,}000 + \frac{6{,}378{,}137}{2} = 8{,}189{,}068.5 \tag{5}$$

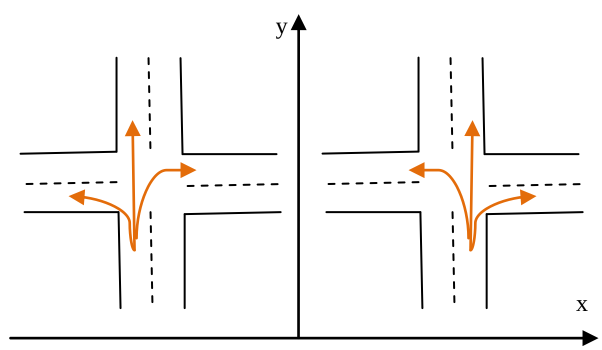


FIGURE 6 Explanation of Left-Hand and Right-Hand Traffic.

Figure 6 explains the difference between left-hand traffic and right-hand traffic. The major difference is that a right turn in left-hand traffic might take more time, just like left turn in right-hand traffic. This paper does not cover all regulations in left-hand traffic since it focuses on the feasibility of using the right-hand traffic simulation model to simulate left-hand traffic. Surprisingly, these two traffic patterns are symmetric by the y axis. All the left-hand traffic regulations can be explained by flopping x coordinates in the right-hand traffic regulations with the following equation.

$$x_{left} = x_{min} + x_{max} - x_{right} = 10{,}000{,}000 - x_{right} \tag{6}$$

To simulate left-hand traffic without changing our simulation models, the x values of input data (links, nodes, zones) should be flopped. After simulation, the x values of output data need to be flopped again. The analysis parameters regarding left-turn/right-turn also need to be switched. The authors tested this methodology with real-world network in Singapore (where vehicles drive on the left).

3.4 Visualization Tools

In order to improve the user experience for users with different background, the authors developed two levels of visualization tools for both link-based macroscopic analysis and vehicle-based microscopic analysis. The macroscopic visualization tool is a web-based application that enables the client to examine the most congested roads from the simulation results. The tool can be accessed at http://gistkona.extranet.ornl.gov/evacmodel/. It provides the capability to visualize simulation results using a spatial interface. It uses OpenStreetMap data to represent the road network for the simulation results. The web-based microscopic visualization tool provides detailed animation of vehicle movement, which helps identify the network choke points during evacuation. This tool can be accessed at http://gisthal.ornl.gov/wwee/. Moreover, the left-hand traffic can also be animated by again flopping x coordinates of vehicle trajectories. The development principle behind these two visualization tools is open source and platform independent. The source code for these two web visualization tools can be accessed on the websites. These tools can be run on different web browsers (such as Firefox, Chrome, and Safari) with WebGL option enabled. The visualization tools can help users re-run their models or test different evacuation strategies.

4. DEMONSTRATION

Several evacuation case studies were simulated in Alexandria, Fort Belvoir, Knox County, Washington D.C., Seattle, Beijing, Berlin, Doha, Singapore, and Taipei to prove the WWEE system's effectiveness. These simulations include five American studies and five global studies. Also, two web applications were used to explain WWEE's visualization capability.

4.1 Macroscopic Visualization and Analysis

The macroscopic visualization data parameters are congestion (posted speed vs. actual speed), delay (min), density (cars/km), speed (km/hour), and time (min), as displayed in Figure 7. The background case study is a selected area in Taipei. Users can view the parameter data in spatial context by 15-minute increments, as a data table with all the parameter results, or as a line chart. Users can select one measure each time from the five parameters to avoid overlay display. By clicking the expand button at the bottom table area, All the links data about the selected measure will be displayed as table. Then users can plot charts for selected parameters as lines. Theses charts can visualize the roads conditions during the selected time period. In addition, users can click on a specific link and display the parameter results for that link. Users can compare the parameter values for a selected link using the composite data tables. All the parameters values are colored based on their representation of the traffic situation on selected links. For example, the red color in congestion parameter means greater congestion. The line uses thickness to present the values. The red line is thicker than the blue line, which means less congestion. Right now, only two case studies data are uploaded on the macroscopic visualization website, Fort Belvoir in Virginia and Taipei in Taiwan.

The simulation in WWEE also generates evacuation curves to visualize the evacuation performance and efficiency. Figure 8 shows the evacuation curves of a selected four-mile radius area in Seattle, with daytime and nighttime evacuation scenarios. In this case, it takes about twelve hours to evacuate people during the daytime, while it costs about seven hours to evacuate the same area during the nighttime. This is because the nighttime population in the selected study area is about 40% of the daytime population. The evacuation curves provide information about evacuation clearance time and evacuation efficiency from a system level analysis.

FIGURE 7 Link-based Macroscopic Visualization Tool.

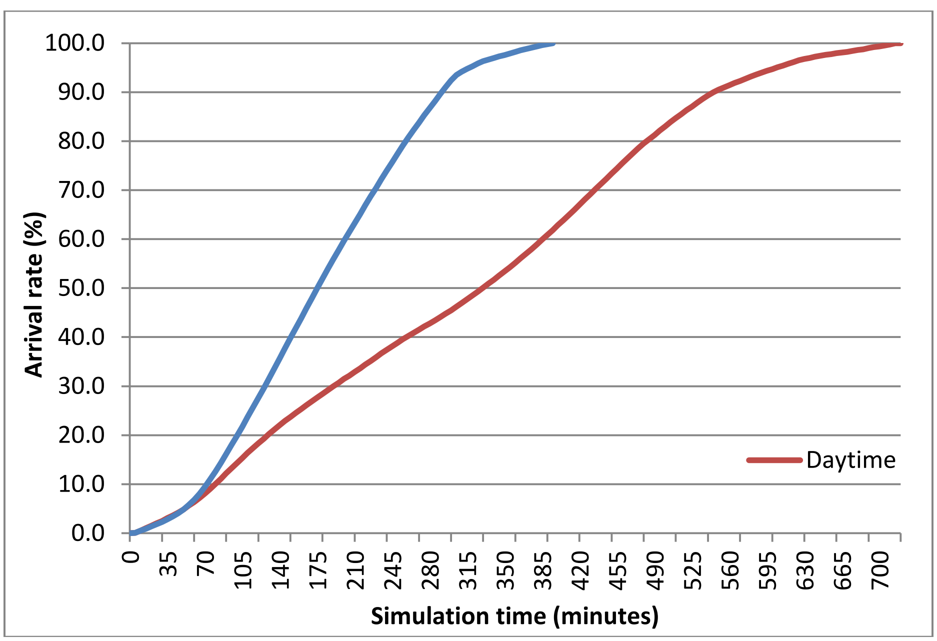


FIGURE 8 Evacuation arrival rates for selected Seattle area during daytime and nighttime scenarios.

4.2 Microscopic Visualization and Analysis

The data from ten case studies data are available on the microscopic visualization website. Figure 9 shows snapshots of microscopic visualization in the US case studies (Alexandria in Virginia, Fort Belvoir in Virginia, Knox County in Tennessee, Washington D.C., and Seattle in Washington). The colored squares represent vehicles. The animation time step ranges from one second to 15 minutes. The 15-minute interval animation produces equivalent outputs to the macroscopic visualization tool. Users can select a certain time to indicate using LandScan daytime or nighttime population data for evacuation simulations. Users can also drag the control button to display results at any time slot during an evacuation simulation. Five case studies of international cities (Beijing, Berlin, Doha, Singapore, and Taipei) are shown in Figure 10. All the selected areas can be cut by administrative boundaries or circles based on evacuation conditions. The areas are all circular area in the UTM projection system, although they might look like ellipses in the web projection system on Google Map. JavaScript, JQuery, and Google Map APIs are used for vehicle plotting and map service. Users can switch to satellite image if they want to know more buildings information or other infrastructures information around congested roads. This vehicle-based microscopic visualization can help evacuation planners and traffic management professionals to identify choke points on the network and plan traffic control strategies correspondingly. The left-hand traffic simulation and visualization can be viewed in the Singapore case study.

5. CONCLUSIONS

The authors have presented the WWEE system, which enables world-wide emergency evacuation simulations with unified data structure, a rapid trip distribution algorithm, left-hand traffic capability, and two levels of visualization. To the authors' knowledge, this is the very first open-source system that enables global users to simulate their evacuation studies with simple data preparation and detailed visualization. With parallel traffic simulation and integration of two visualization tools, WWEE can provide an easier-to-use and computationally efficient system for megaregion evacuation simulations and big transportation data visualization.

There are still some challenges behind this system. First, most existing traffic simulation models are built on Traffic Analysis Zones (TAZ) zoning technique. The WWEE uses high-resolution LandScan population cells (LPC). The transformation from TAZ-to-TAZ OD matrix to LPC-to-LPC OD matrix needs more study if this system is to be expanded to day-to-day regular traffic simulations. Second, the simulation network data comes from OpenStreetMap, but the visualization tools are built on Google Maps. There are some data matching and accuracy issues to overlap these two data resources. This can be improved with constant updating by the open-source OpenStreetMap community and commercial Google Maps teams. Third, the evacuation travel demand model in the WWEE is simple and lack of effective data to generate the realistic travel demand for each city in the world. The local users know much better about their neighborhood situation might easily identify some implausible results at specific places. These challenges also encourage researchers from computer science, emergency management, data science and other interdisciplinary domains to contribute to the big data based transportation modeling, simulation, and visualization studies.

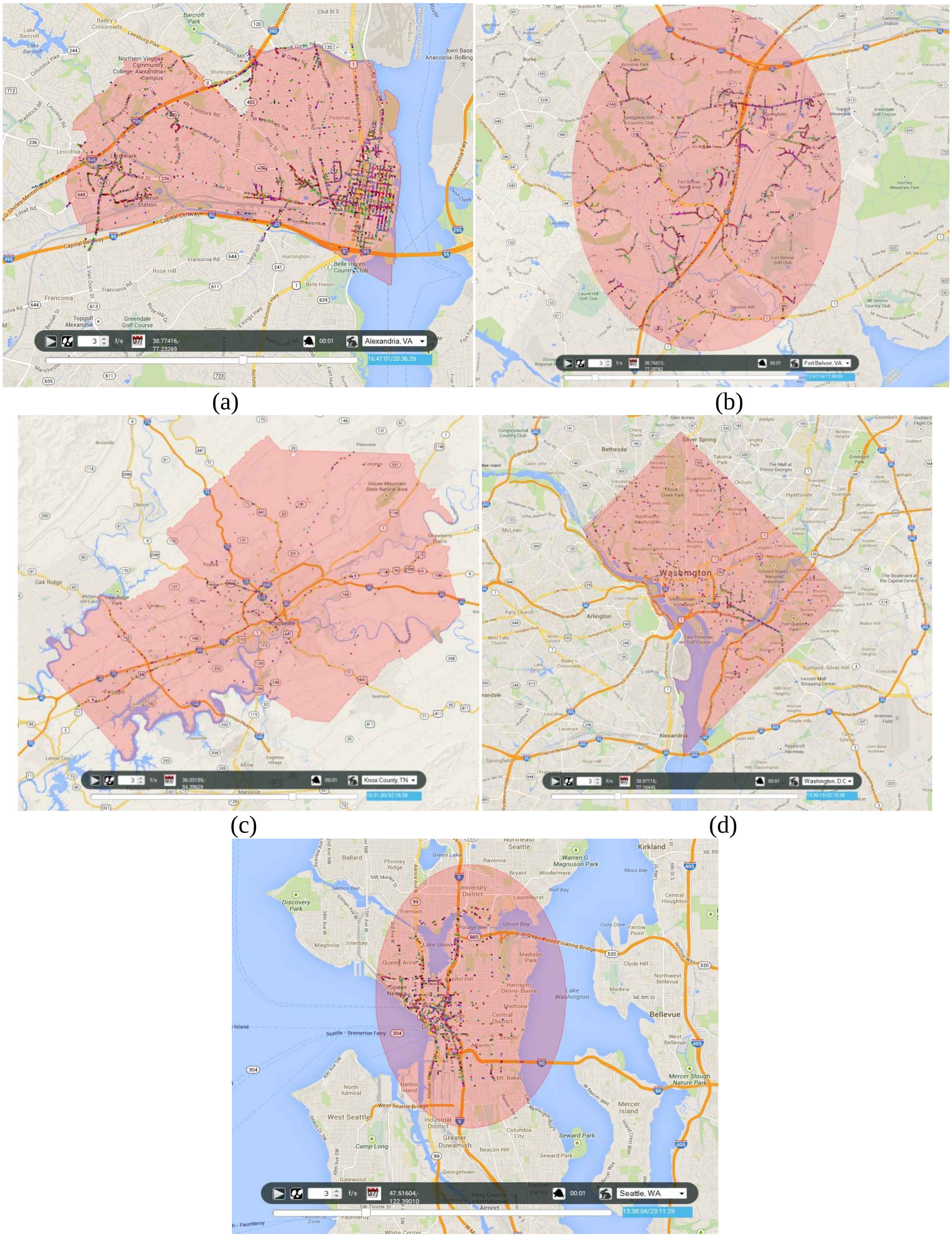
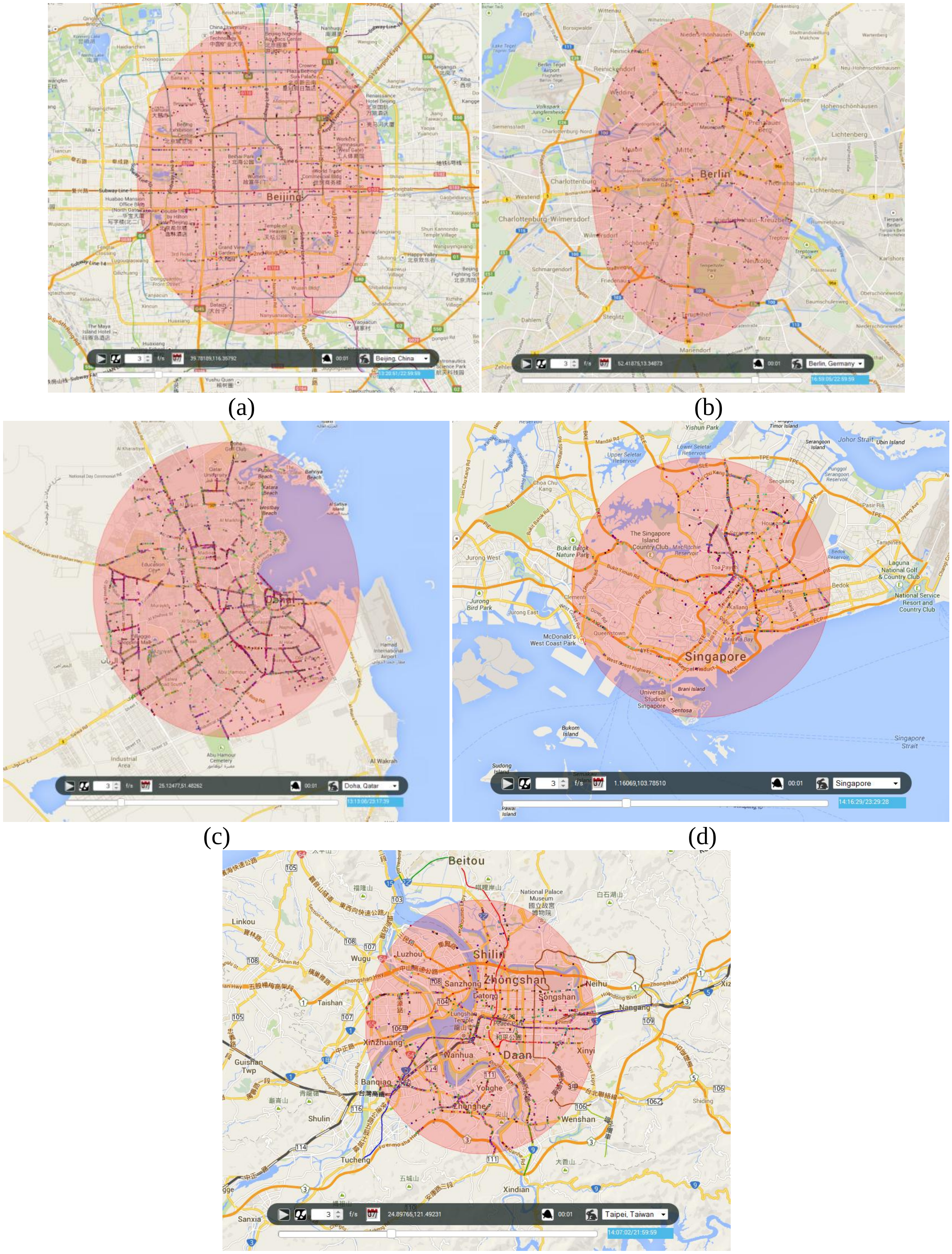


FIGURE 9 Vehicle-based Microscopic Visualizations in five US case studies: (a) Alexandria, VA (b) Fort Belvoir, VA (c) Knox County, TN (d) Washington D.C. (e) Seattle, WA.



(a) (b)

(c) (d)

(e)

FIGURE 10 Vehicle-based Microscopic Visualizations in five global case studies: (a) Beijing, China (b) Berlin, Germany (c) Doha, Qatar (d) Singapore (e) Taipei, Taiwan.

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