Rapid Emergency Evacuation Planning/Assessment for Tourist Attractions and Isolated Communities

Research Final Report from the University of Tennessee
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DISCLAIMER

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16. Abstract

This study proposed, implemented, tested, and demonstrated an emergency evacuation modeling framework called T-REX, or Tennessee Rapid Evacuation micro-simulation. The purpose of the effort is to provide a simple workflow for the implementation in smaller isolated communities or tourist attractions where we often observe 1) captive transportation network options and exit capacity, 2) significant number of visitors unfamiliar with local hazards or evacuation options, and 3) limited resources for planning, modeling, or executing complex evacuation operations. Five case studies were conducted for Gatlinburg, Manchester, Downtown Nashville, Lynchburg, and Wears Valley area of Tennessee. More in depth presentation and discussion on the results of the fifth site at Wears Valley was documented in Chapter 4 because it was the most recent occurrence and because the team was able to obtain detailed feedback from local EMA personnel. Key findings of the study include 1) the demonstrated timely and rapid implementation of T-REX framework for modeling a handful sites in the state of Tennessee; 2) the economical implementation of the framework because each component was off-the-shelf, tested, and essentially free to use by the public; 3) the framework has the flexibility to be implemented by different agencies with past experience or current preference if different simulation software, population data, or transportation network were to be employed; and 4) the results from T-REX process are to be compared relatively and interpreted carefully by researchers and practitioners to provide insightful recommendations to decision-makers. This study also looked into future implementation means for benefiting other sites in and around the State of Tennessee. The funding vehicles of LTAP and UTAP are suitable for engaging university researchers to help local jurisdictions.

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Mr. Joe Ayers of Sevier County EMA provided valuable feedback at multiple stages of the study. Mr. John Stanford performed important research activities in the early part of this study including contacting various agencies and assessing multiple study site candidates. Their participation kept this study well-grounded to real-world applications.

Executive Summary

This study proposed, implemented, tested, and demonstrated an emergency evacuation modeling framework called T-REX, or Tennessee Rapid Evacuation MicroSimulation. The purpose of the effort is to provide a simple workflow for the implementation in smaller isolated communities or tourist attractions where we often observe 1) captive transportation network options and exit capacity, 2) significant number of visitors unfamiliar with local hazards or evacuation options, and 3) limited resources for planning, modeling, or executing complex evacuation operations.

Five case studies were conducted for Gatlinburg, Manchester, Downtown Nashville, Lynchburg, and Wears Valley area of Tennessee. Using state-of-the-art high-resolution population distribution datasets from ORNL's LandScan USA, employing OpenStreetMap's highway network, and coding everything into the SUMO microsimulation software, this research team modeled and evaluated an array of evacuation scenarios for the five sites. More in depth presentation and discussion of the results of the fifth site at Wears Valley was documented in the Chapter 4 because it was the most recent occurrence and because the team was able to obtain detailed feedback from local EMA personnel.

Key findings of the study include 1) the demonstrated timely and rapid implementation of T-REX framework for modeling a handful sites in the state of Tennessee; 2) the economical implementation of the framework because each component was off-the-shelf, tested, and essentially free to use by the public; 3) the framework has the flexibility to be implemented by different agencies with past experience or current preference if different simulation software, population data, or transportation network were to be employed; and 4) the results from T-REX process are to be compared relatively and interpreted carefully by researchers and practitioners to provide insightful recommendations to decision-makers.

There are some challenges and lessons learned in the process of the study primarily related to recruiting the participation of local jurisdictions and soliciting feedback from them. The COVID-19 pandemic that coincided with the study period and the work-from-home aspect also slowed the progress of such. However, towards the later part of the project participation and feedback were provided by a keep stakeholder for the two of the study sites.

Finally, this study also looked into future implementation means for benefiting other sites in and around the State of Tennessee. The funding vehicles of LTAP and UTAP are suitable for engaging university researchers to help local jurisdictions. Perhaps TDOT could consider funding a number of such projects to test implement T-REX in the near future.

Key Findings

- **Timely Implementation**: The T-REX framework proposed and tested in this study demonstrated that the research team was able to complete the precatory work for utilizing a microscopic simulation software package in a timely fashion. Evacuee information in terms of both daytime and nighttime populations and locations within the evacuation zone were imported from LandScan USA and the transportation network coded directed from OpenStreetMap. It does take some time to assign evacuation destinations for each evacuee and the time they are loaded onto the network based on their locations in the network. Once all input items are ready, the SUMO package can simulate the selected scenario within hours depending on the size of the network, the number of evacuees, and the complexity of the scenario. In general, the modeling process for each scenario can be conducted in a timely fashion.

- **Economic Considerations**: All components selected for implementation in this study, from the population database (LandScan) to the transportation network (OpenStreetMap) to the simulation engine (SUMO), are open, tested, off-the-shelf, and free to the public. This makes it more feasible to implement for local agencies.
- **Flexibility in the Framework**: T-REX is a framework that can be implemented with different component choices. Alternative components such as Streetlight population data, ESRI GIS maps, and VISSIM simulation package or similar can all be used to substitute the open and free components we used in this study. Agencies with models readily developed or preferences in certain databases, could implement T-REX with their own "flavor" with similar success.
- **Results Interpretation**: The simulation of the myriad scenarios at various study sites yielded animation clips, congestion maps, bottleneck locations, traffic control strategies, and traffic operation statistics. These should be used in relative terms in comparison to other similar scenarios at the same sites as opposed to in absolute terms in comparison to actual field evacuation situations. The modeled results could provide insights towards identifying hot spots that may get congested and useful strategies for evacuation management. The experiences and local knowledge from first responders and stakeholders are essential in guiding the interpretations and subsequent policy and operational decisions based on the results.

Key Recommendations

- **Technology Transfer through LTAP/UTAP**: A major objective of all of TDOT's research projects is technology transfer or putting the results and findings of the sponsored efforts to practice. In this case, as demonstrated in the case studies, the resultant T-REX framework can indeed be implemented in selected locales. The long-standing Local Transportation Assistance Program as well as the newly established University Transportation Assistance Program are two conduits for such implementations. Through these programs experienced researchers at, for example, the University of Tennessee could follow the T-REX workflow to collect necessary data, code the pertinent transportation network, employing off-the-shelf simulation models, and perform evacuation modeling and analysis tasks on computer hardware without extra costs to small local communities.
- **Other Implementations**: In addition to wildfire and other cases studied herein, additional scenarios such as major transportation hazmat spills and mishaps, school and public facility under terror attack, tornado at major sport events, and a number of other

hazards can all be evaluated with T-REX type of framework and workflow. It is important that stakeholders and local jurisdictions could participate to provide feedback, to be familiar with the process, and, in general, to provide guidance to the appropriate representation of various characteristics of the population, the network, the hazards, and the countermeasures available to the area.

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Glossary of Key Terms and Acronyms

AADT	Average Annual Daily Traffic
AM	Ante meridiem, which means “before noon.”
API	Application Programming Interface
ATMS	Advanced Traffic Management System
AVO	Average Vehicle Occupancy
CBD	Central Business District
CCP	Connected Citizen Program
CMAQ	Congestion Mitigation and Air Quality
DHS	Department of Homeland Security
DMS	Dynamic Message Sign
DOT	Department of Transportation
EOQ	End of Queue
EMA	Emergency Management Agency
ETRIMS	Enhanced Tennessee Roadway Information Management System
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FSSP	Freeway Service Safety Patrol
GFD	Gatlinburg Fire Department
GPS	Global Positioning System
HELP	TDOT’s Highway Incident Response Unit
JSON	A data file format system
LandScan	A global population distribution dataset developed at ORNL
Locate/IM	Locate Incident Management
LTAP	Local Transportation Assistance Program
MAE	Mean Absolute Error
MOE	Measure of Effectiveness

MPH	Mile per hour
NFL	National Football League
NPMRDS	National performance management research data set
OD	Origin and Destination
OREMS	Oak Ridge Evacuation Modeling System developed at ORNL
ORNL	Oak Ridge National Laboratory
OSM	OpenStreetMap, a crowdsourced map of the world
PCMS	Portable changeable message signs
PM	Post meridiem, which means “after noon.”
PTQ	Protect the Queue
Python	An interpreted object-oriented high-level programming language
RDS	Radar Detection System
RMSE	Root Mean Square Error
RTMS	Remote Traffic Microwave Sensors
SUMO	A microsimulation software: Simulation of Urban MObility
TAZ	Transportation Analysis Zone
TDOT	Tennessee Department of Transportation
THP	Tennessee Highway Patrol
TIM	Traffic Incident Management
TMC	Traffic Management Centers
TN	Tennessee
TRB	Transportation Research Board
TREX or T-REX	Tennessee Rapid Evacuation MicroSimulation
UTAP	University Transportation Assistance Program
VISSIM	Multimodal traffic simulation software developed by PTV
WAZE	A subsidiary of Google company that collects real-time traffic information like travel times, and traffic incidents from users.

Chapter 1 Introduction

1.1 Scope of Study

Each year, the U.S. experiences hundreds of significant disasters and emergencies that prompt intervention from the Federal Emergency Management Agency (FEMA) in the form of financial and logistical support. Additionally, numerous other emergency events may not receive national declarations but still pose grave risks to human life. Tennessee is no stranger to such crises, frequently experiencing severe storms, floods, and fires. The state has also been affected by other weather-related calamities like tornadoes, severe ice storms, snowfalls, and even hurricanes that have been declared national emergencies. Notable examples include the severe flooding in Knoxville in 2019 (DR-4427) and Nashville in 2010 (DR-1909), as well as the devastating wildfires in Gatlinburg in 2016 (DR-4293), all of which received presidential disaster declarations.

Figure 1-1 Disaster scenes.

In numerous officially recognized and under-the-radar emergencies, prompt and large-scale evacuations often emerge as the critical immediate response for safeguarding the public. However, pulling off a seamless evacuation operation is a complex endeavor that demands meticulous planning and robust management, underpinned by the right tools [16]. The Gatlinburg Fires in 2016 painfully revealed deficiencies in alternative transportation routes in the affected regions. While some local governments might have formal or ad-hoc evacuation procedures in place, executing them can present a multitude of challenges.

- ***Lacks Comprehensive Plan or Planning Process*** **–** Bigger cities often have some type of evacuation blueprint, but smaller towns that don't fit the "high-threat, high-density" profile outlined by DHS and FHWA [24] frequently lack adequate evacuation preparedness. Jurisdictions need not just plans for different contingencies but also a sustained process for keeping those plans up to date.
- ***Lacks Sophisticated and Comprehensive Modeling Tools*** **–** Even when some form of evacuation plan exists, it is often the product of discussions among well-meaning local leaders, law enforcement agencies, and urban planners rather than informed traffic specialists. This leaves untested the practicality of the plan and various emergency scenarios, along with potential solutions. Specialized simulation software can offer deeper insights but comes at a high cost.
- ***Steep Learning Curve with Modeling Tools*** **–** For larger jurisdictions that do invest in sophisticated simulation solutions, there's often a time-consuming learning curve involved. Coding the complete roadway network, identifying and encoding evacuating populations, and creating multiple emergency scenarios can be a lengthy process. Gathering the required data for an initial simulation run can take several months for a smaller jurisdiction.
- ***Lacks Significant Resource Commitment*** **–** Utilizing advanced simulation tools, which are generally not tailored for mass evacuation procedures, can strain the resources of smaller municipalities due to the substantial commitment of time, staff, and hardware. Given that continuous planning is a requisite for effective emergency management, the enduring obligation can prove to be intimidating or burdensome.

To this end, this study developed a framework dubbed *T-REX*, or Tennessee Rapid Evacuation MicroSimulation, to mythologically code the roadway network, identify the likely evacuees and their location in the affected area, and expeditiously model various evacuation scenarios of these evacuees on the available roadway network. For the purpose of the study, touristy and smaller urban communities are the primary considerations because larger urban areas typically already have many alternative evacuation routes and comprehensive plans. But smaller areas tend to lack the resources and data needed to perform detailed traffic simulations. T-REX utilizes available, typically off-the-shelf, transportation network database and day/nighttime population at high resolution to create input data needed for sophisticated microsimulation, such as VISSIM and SUMO. Various scenarios can be modeled quickly to help evaluate existing plans, generate new evacuation plans, identify operational problems during evacuation, and provide "what-if" type options for scenario planning.

For the purposes of this research, several locations in Tennessee were analyzed, namely: i) Sevier County, encompassing the region impacted by the Wears Valley Wildfire in April 2022, ii) Central Nashville and its adjacent areas, iii) Manchester, home to the Bonnaroo Music and Arts Festival, and iv) Lynchburg, renowned for tourist sites like the Jack Daniel's factory.

The T-REX framework has showcased its adaptability across various Tennessee communities, affirming its potential for universal application in both tourist hotspots and urbanized areas. Its versatility suggests a promising avenue for collaboration with the Tennessee Department of Transportation (TDOT) to assist underserved communities in evacuation planning. Furthermore, this project underscores the pivotal role of evacuation loading rates in dictating evacuation efficiency. It also introduces novel evacuation approaches anchored in percolation theory, poised to boost community safety and readiness during emergencies.

1.2 Study Objectives

To address the aforementioned challenges and provide an evacuation planning framework that can be used for smaller and less resource-rich communities and municipalities, the following objectives were identified for this study.

- ***Objective 1 – To Develop an Easy-to-Use Modeling Workflow***. As mentioned, most traffic simulation tools require significant preparatory efforts and data collection investment before they can be used for real-world evacuation scenario modeling. The primary objective of this study is to develop an easy-to-use modeling workflow that can be ready to model, with all the transportation network and at-risk population data coded in a timely fashion, in a much shorter time frame.
- ***Objective 2 – To Improve Preparedness***. By providing an easy-to-use modeling workflow and demonstrating it for real at-risk sites, this study aims to promote evacuation planning process, enhance the capability for evaluating alternative evacuation tactics, and improve the preparedness of locales with potential emergency risks and limited resources.
- ***Objective 3 – To Help Identify Critical Infrastructure and At-Risk Populations/Locations***. Through case studies T-REX, the primary product of the project, can help identify infrastructure links that are likely to become evacuation traffic bottlenecks or can significantly impede the evacuation operations should any incident occur on these links. Locations and the population that could be ill-served by certain evacuation strategies may also be identified and, subsequently, remedied.
- ***Objective 4 – To Provide Insights for Community Engagement.*** With the ability to assess multiple scenarios, e.g., compliance to mandatory evacuation orders and evacuation route/destination assignments, and with its GIS-based graphical animations, T-REX has the ability to convince the at-risk public and the local decision-makers to opt of safer and more efficient operational strategies.
- ***Objective 5 – To Plan for Future Deployment*** – Scenarios towards the implementation of T-REX are identified to include a technology transfer demonstration of T-REX to TDOT and appropriate local jurisdictions. Considerations also include incorporating new capabilities based on the feedbacks from potential users.

Chapter 2 Literature Review

Many traffic simulation tools have been developed to model mass evacuation operations since as early as 1980's [30]. Early attempts at simulation, on much slower computers using less versatile programming languages with limited understanding of traffic flow characteristics, were met not surprisingly with mixed, if any, success. Nevertheless, simulation has been recognized as a sensible and promising direction for studying evacuation operations, which are rare events hard to observed or replicate. In subsequent years, a number of simulation models were developed including ORNL's OREMS model, which Han et al applied for evacuation strategy evaluations for Army's Blue Grass Chemical Stockpile, hurricane evacuations [16], and for using transit vehicles to evacuate flooded communities in North Carolina coastal areas [28]. While these simulation tools were specifically designed for evacuation purpose, many simulation-based evacuation studies began to utilize commercially available general-purpose software, such as VISSIM. These packages can be expensive for non-academic use and challenging to implement due to a steep learning-curve and a need for detailed input information.

Another direction of evacuation planning is to optimize route assignment for evacuees in each evacuation zones, typically the size of common TAZ used in traditional transportation planning exercises. Until early 2000s, it is common for evacuation planers to assign all evacuee from the same evacuation zone to a single destination, chosen by a committee based on experience and consensus, outside the evacuation area. By, somehow, optimizing the operation, the best route, typically a major arterial, can be determined for a large number of evacuees going form the same origin (O) to the same destination (D). The major breakthrough came in 2006 when Han proposed the novel concept of "super node" for simultaneously optimizing the destination assignment and route assignment. This takes guesswork out of destination assignment by committee and significantly improves the solution [17]. The next breakthrough came one year later when Dr. Han asked and answered the question of "What is an efficient evacuation operation?" by proposing a set of measures of effectiveness (MOE) that researcher could use to optimize the evacuation for different types of life-threatening disasters [16].

Evacuations under disastrous conditions are time sensitive; optimizing the use of the existing transportation network capacity during emergencies is crucial to traffic efficiency. In the context of vehicle-based evacuation, evacuation times are dependent on the network's traffic flow size; as traffic density increases, the evacuation times escalate non-linearly, leading to traffic congestion and potentially resulting in network deadlock.

The existing body of evacuation research extensively delves into the topics of travel demand modeling [19, 7, 27, 31, 30] and traffic assignment in evacuation scenarios [24, 6, 9, 4, 17], predominantly treating these problems from a planning point of view. In the current landscape of research on disaster response and management, our study takes a unique perspective by focusing on the rapid evacuation of traffic from a Central Business District (CBD) during an emergency. This is a distinct scenario that significantly diverges from traditional evacuation planning approaches, which typically address events that unfold over an extended period of several days or weeks. In this evacuation context, marked by the potential for rapid congestion and increased safety risks, we approach this urgent evacuation task more as a traffic control problem than a conventional planning task.

In response to an emergency, traffic can be loaded onto the network at different rates, often achieved through the scheduling of evacuation trips and managing the loading process to optimize the performance of the network [25]. In the extreme case, where every evacuee leaves simultaneously, i.e., surge loading, this would lead to premature congestion and spillback [1]. The loading rate plays a significant role in congestion build-up and overall evacuation efficiency [16]. There are some studies on the staged evacuation [8, 25, 14, 12], where all individuals are presumed to evacuate, and the only decision is how to distribute this evacuation demand over time to reduce the network clearance time. Bish et al. [5] used a loading curve in the modeling framework to determine when to initiate the evacuation of a zone; [31] studied the optimization of the issuance of orders to achieve a reduction in risk across the region. However, the representation of traffic flow in these model-based approaches tends to be more aggregated in nature.

To the best of our knowledge, there still lacks a large-scale microscopic evacuation simulation in the study of emergency evacuation, which is unfortunate given the loss of detailed traffic information, especially those evacuation-specific performance metrics, which will be discussed shortly in the paper. Large-scale microscopic simulation is arguably the only way to capture complex system behaviors in congestion, not demonstrated by any existing macroscopic traffic flow models. To bridge this gap, this study uses a microscopic simulation tool, Simulation of Urban MObility (SUMO) [2], to investigate the effects of traffic loading during emergency evacuation. Microscopic simulation enables us to capture the complex behavior occurring amidst traffic congestion, helping us interpret the network's congestion patterns through the lens of percolation theory.

Traffic control during emergency evacuations remains a challenging issue, requiring further investigation. Recently, percolation theory has been introduced into traffic flow theory [21, 31, 23], ushering in new possibilities for innovative evacuation control strategies. Our study delves into percolation-based traffic monitoring and control techniques for better evacuation management.

Chapter 3 Methodology

3.1 T-REX Framework

Typically, to carry out a microscopic evacuation modeling effort for a large study area, significant time and human resources would be required to collect detailed evacuation population data, to code the detailed transportation network for the study area and the surrounding region, to identify suitable evacuation hazards and corresponding response scenarios, to identify potential bottlenecks and trouble spots, to optimize the traffic management strategies, to communicate the findings to stakeholders and decision-makers, and to seek feedbacks and incorporate into the planning process. These steps and activities can to exceedingly time-consuming and even cost-prohibitive for smaller jurisdictions. To that end, T-REX is a comprehensive framework that comprises crucial components including Evacuee Population Distribution Database, Transportation Network for the evacuation operation, a Mass Evacuation Scenario Base with suitable cases to be considered and modeled, the MicroSimulation Engine that is a computer software, and subsequent Support for Technology Transfer., see Figure 3-1. Most of these components are tested, readily available, and mostly affordable. The following sections will introduce these components.

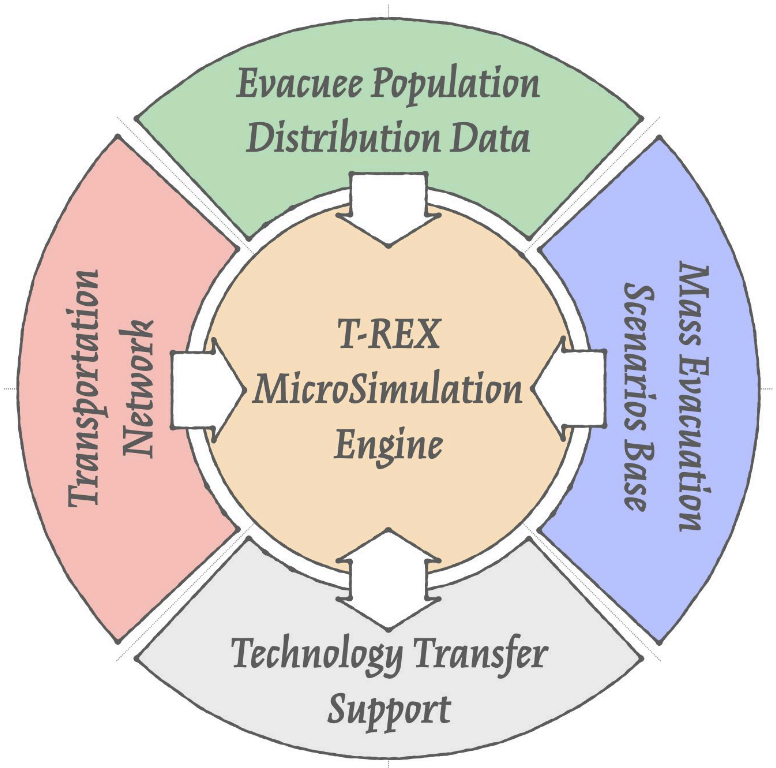


Figure 3-1 Visualization of T-REX Framework.

3.2 Population Distribution Data

Traffic simulation generally required an origin-destination (OD) type of input to simulate real-world traffic. However, evacuation modeling posed a more significant challenge. Traditional planning often relied on coarse Traffic Analysis Zones (TAZ-level OD), but for more precise modeling, especially to account for the seasonal variations in tourist traffic, we employed ORNL's LandScan USA population distribution database for identifying evacuee origins. LandScan USA employs a dasymetric population distribution model to represent the spatial and temporal distribution of individuals. The database integrated multiple data sources, such as census data, high-resolution imagery, transportation infrastructure, lidar data, and building information, to generate population estimates. An example of this data was demonstrated in Figure 3-2, which displayed LandScan USA population data for downtown Nashville, Tennessee. The color scheme highlighted the population density in each 90x90 meter raster. The data clearly showed a higher population density in Nashville's center during the day, which shifted towards the residential periphery at night.

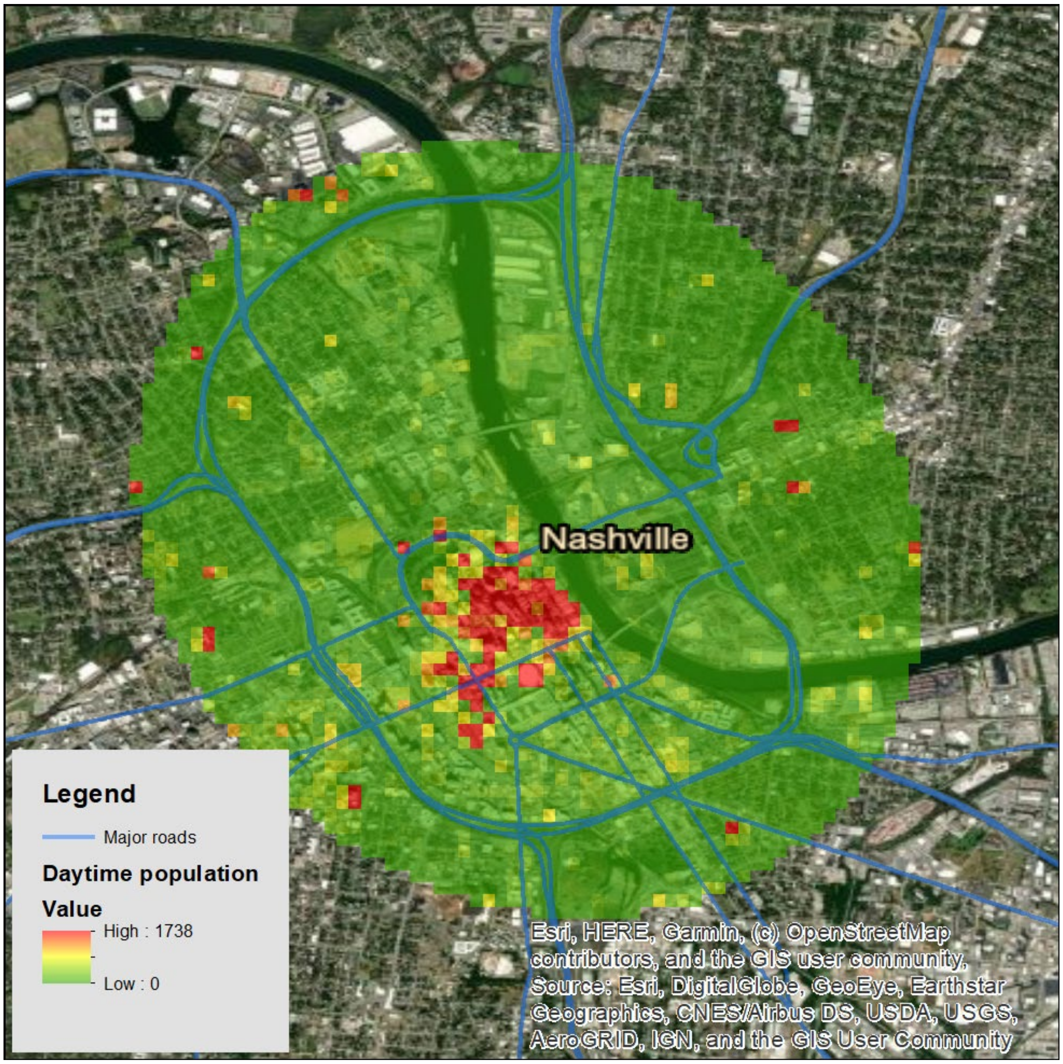


Figure 3-2 LandScan USA day time population data.

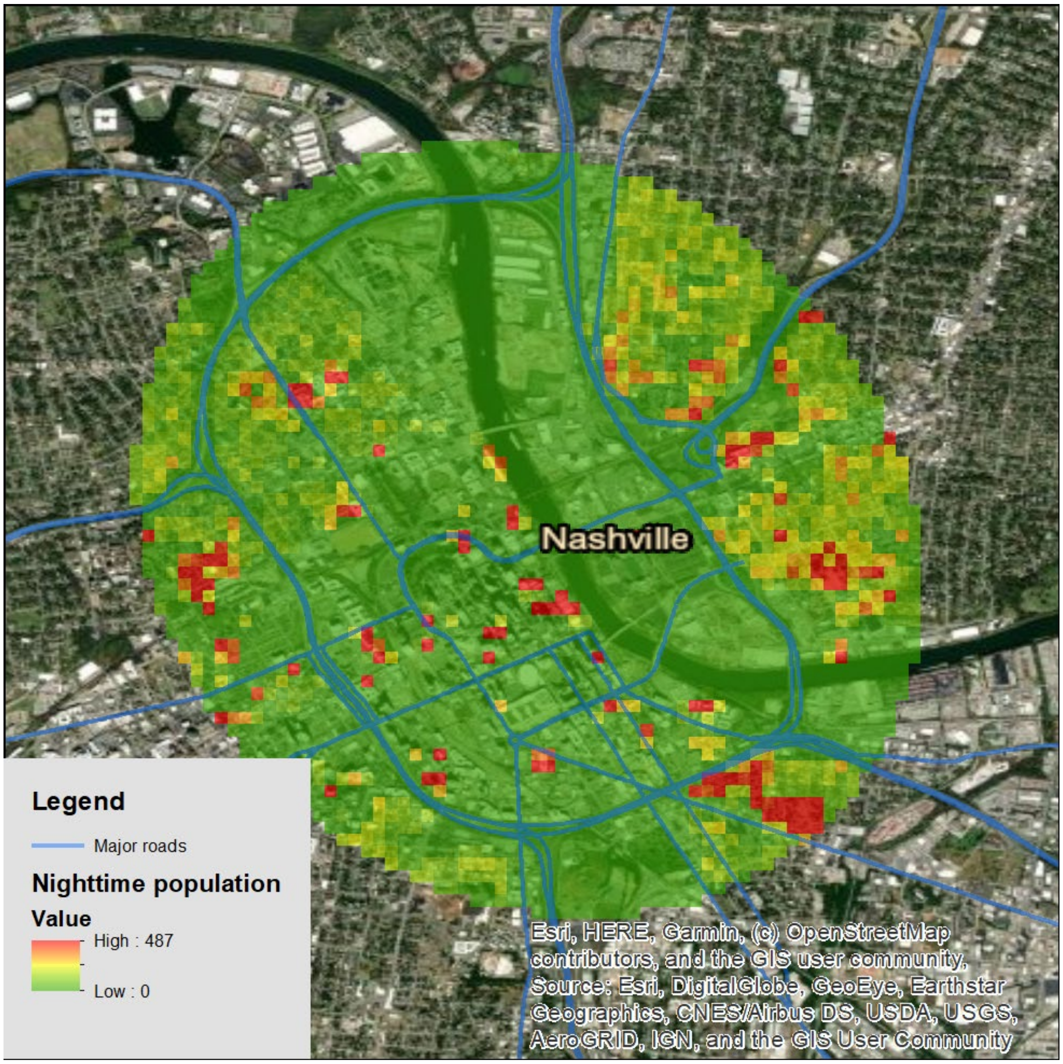


Figure 3-3 LandScan USA night time population data.

The population data is represented in raster format with a 90-meter by 90-meter spatial resolution, providing population counts for both day and night. This high-resolution dataset enabled us to allocate evacuees to the nearest exit more accurately. Furthermore, the availability of both daytime and nighttime data allowed us to create disaster plans tailored to different times of day.

3.3 Transportation Network Generation

Network generation is often the first step in creating a realistic simulation. In our project, we leveraged Python scripting to interact with OpenStreetMap (OSM). With this setup, users can easily zoom into a geographical area of interest, capturing all the nuances of its road and transport systems. The data from OSM is comprehensive, including details about road types, intersections, public transportation routes, and more.

Importing infrastructure data from OSM into SUMO is not a one-size-fits-all process. Different options can significantly affect the final simulation. Here are some of the key options that we can toggle during the import process:

- **Add Polygon**: By default, this option is enabled, importing all kinds of roads and pathways, including cycle paths, footpaths, and railways. This feature provides a complete representation of the traffic ecosystem but can make the simulation more complex.
- **Left-hand Traffic**: For regions where left-hand traffic rules are standard, enabling this option will automatically set the network accordingly. If this feature doesn't automatically detect the region, manually checking this box ensures accurate traffic flow.
- **Car-only Network**: This option narrows down the network to only include roads that allow passenger cars. This simplification can be beneficial for focusing on specific traffic scenarios or for handling large networks more efficiently.
- **Import Public Transport**: When this is selected, the simulation will include public transport stops and routes. Although these are based on real-world data, the schedules are synthetic but still provide a close approximation of public transportation flow.
- **Demand-checkbox for Bicycles**: Enabling this option will add extra bicycle lanes to the simulation where OSM has this data, providing a more nuanced model of non-motorized traffic.
- **Demand-checkbox for Pedestrians**: Activating this option will generate sidewalks and pedestrian crossings, further enriching the simulation to consider the broadest range of road users.

Figure 3-4 Network building using Python and Open Street Maps.

We can create a highly realistic and specific traffic simulation model with high granularity in control. This adaptability makes it well-suited for addressing the needs of various projects, including but not limited to those focused on evacuation traffic management, allowing for fine-tuned adjustments to accommodate multiple traffic scenarios.

After the initial setup and option selections, we'll have an editable SUMO network file. This file serves as the base for building evacuation scenarios. In SUMO terms, the network is essentially a directed graph where:

- **Nodes**, commonly known as "junctions," represent intersections.
- **Edges** are the roads connecting these junctions and are unidirectional.
- **Lanes**: Each edge is made up of one or more lanes, each having attributes like position, shape, and speed limit.
- **Traffic Light Logic**: This is linked to junctions and controls the traffic light cycles.
- **Junctions**: These contain right-of-way rules that govern how vehicles maneuver through the intersection.

- **Lane Connections**: This describes how lanes are connected at the junctions or nodes.

Depending on the input formats and options selected during setup, the network file may also include:

- **Districts**: These are zones within the simulation that can be used for specifying origin-destination matrices.
- **Roundabout Descriptions**: These describe the geometry and rules governing roundabouts in the network.

This structured and detailed network file provides the groundwork for creating multiple, scenario-specific traffic models, such as those required for effective evacuation traffic management. We will present the network for each of our site in the following section.

3.4 Mass Evacuation Scenarios and Case Studies

Evacuation scenarios are typically affected by the evacuation site characteristics, the nature of the hazards, the population demographics, and available transportation modes and their networks, and the traffic control or management capabilities of the local agencies. For this project, we look at a total of five case studies in different locales with different considerations including the potential evacuees in the transportation networks of the vicinities of Gatlinburg, Manchester, Downtown Nashville, Lynchburg, and Wears Valley, TN. While Gatlinburg and Wears Valley are more susceptive to the recurring risk of wildfires, the other locales could face the danger of tornado, flooding, as well terror attacks.

3.4.1 Gatlinburg Fire of 2016

In the scope of our research, the first site of significance is Gatlinburg, Tennessee, notably impacted by the Gatlinburg Fire of 2016. On November 28 of that year, an unprecedented wildfire fueled by drought and high winds ravaged the Great Smoky Mountains National Park, Gatlinburg, and surrounding Sevier County. The fire left the community with extensive physical and emotional scars, decimating homes, businesses, and landscapes within hours. However, 2016 was not an isolated incident. The Gatlinburg Fire Department (GFD) has responded to multiple wildfires over the years, including the English Mountain fire in 2012 that destroyed 48 units, the Black Bear Cub Way fire in 2013 where over 70 cabins were damaged or destroyed, and the Gatlinburg Summit Condominium fire in 2014. These recurring events highlight the urgent need for a responsive evacuation plan [15].

Given the frequent and severe fire-related incidents, the development of an adaptable and reliable evacuation model is crucial for Gatlinburg and Sevier County. Our study employs the T-REX framework, incorporating Evacuee Population Distribution data, Transportation Network, and Mass Evacuation Scenario Base, to generate rapid and high-fidelity evacuation scenarios. This framework is particularly suitable for smaller, at-risk communities like Gatlinburg. It not only facilitates technology transfer but also aids in storytelling, helping to translate the data into actionable plans for emergency managers and responders.

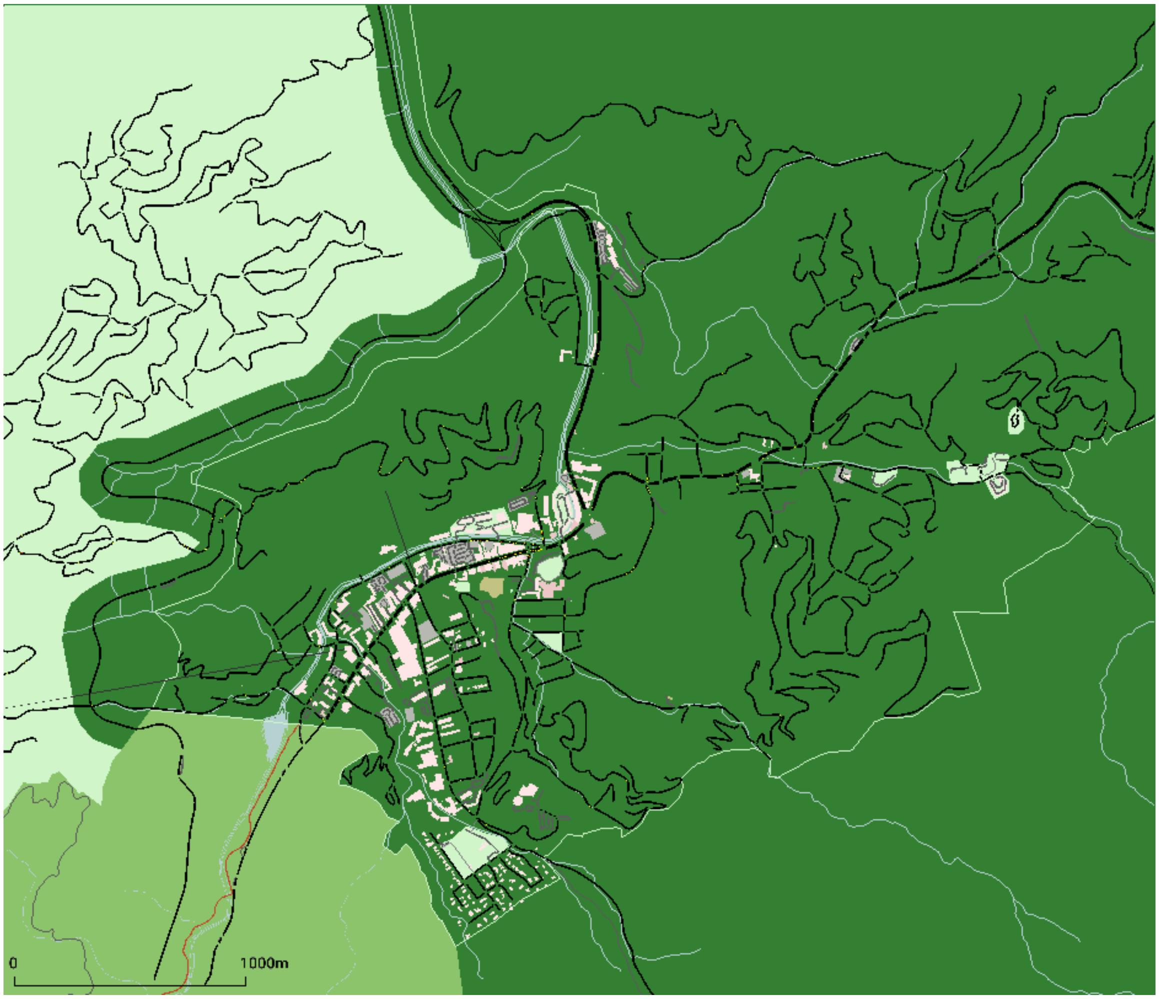


Figure 3-5 Gatlinburg, TN Study Site in SUMO.

3.4.2 Manchester and Bonnaroo Festival

The second study site under consideration is Manchester, Tennessee, home to the Bonnaroo Music and Arts Festival. This annual four-day event transforms Manchester and rural Coffee County into a bustling hub, drawing over 80,000 attendees to Great Stage Park, affectionately known as "The Farm" among festivalgoers. The festival's immense popularity, frequently resulting in sold-out four-day passes, elevates the event into a densely populated four-day summer camp. This sudden influx places significant strain on the local transportation infrastructure, heightening the need for well-coordinated evacuation plans in emergency situations.

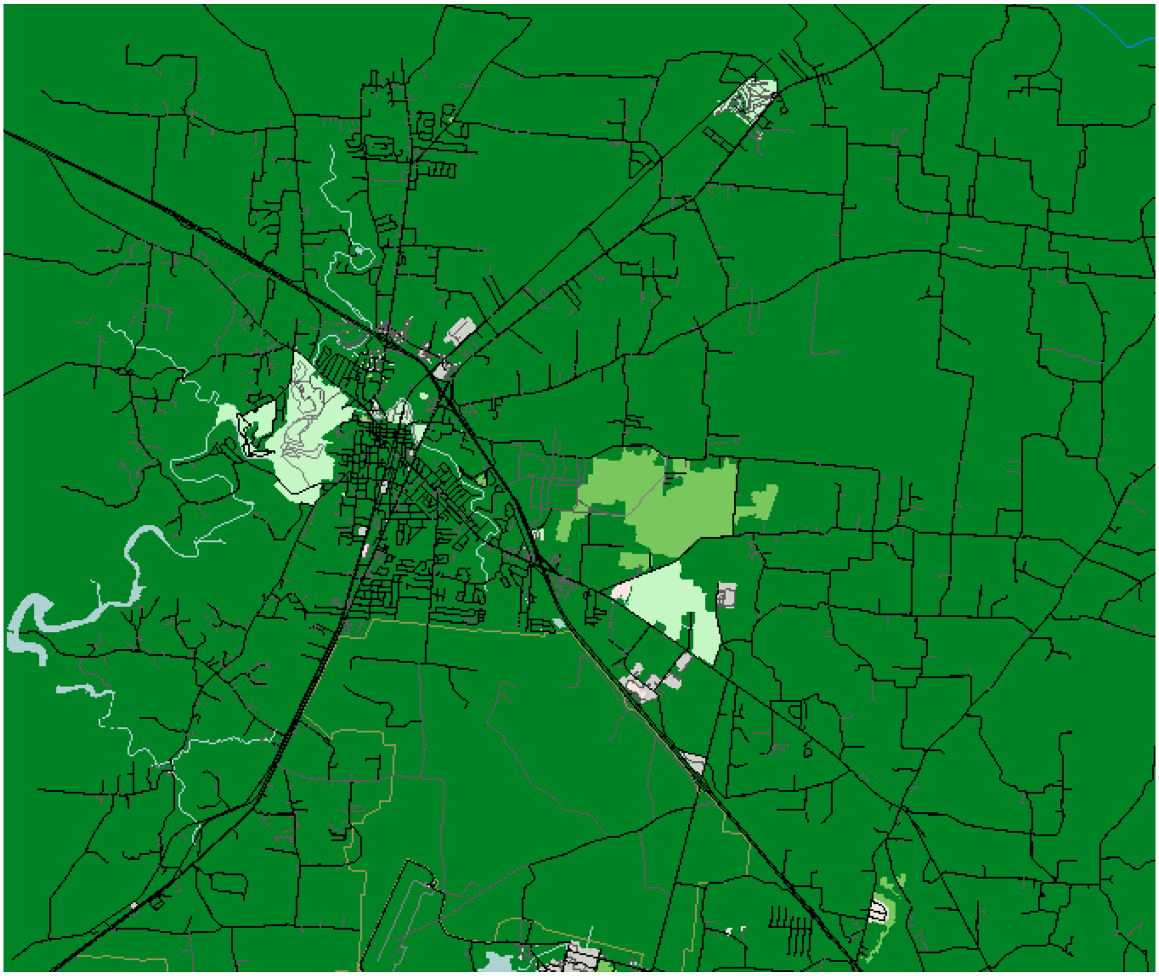


Figure 3-6 Manchester, TN Study Site in SUMO.

The T-REX framework demonstrates its strengths in such dynamic environments. Given its ability to process high-resolution population data, it is well-suited to adapt to Manchester's rapidly fluctuating population during the festival period. Whether it's an emergency at the festival or other unforeseen circumstances requiring mass evacuation, the framework's ability to quickly generate accurate scenarios is invaluable. Manchester's traffic landscape adds another layer of complexity to its emergency preparedness needs. Interstate 24 skirts the northeast perimeter of the city, accessible via Exits 110, 111, and 114. A unique feature is Exit "112," a "temporary exit" that directly leads from I-24 into the Bonnaroo Music Festival site. U.S. Route 41 and Tennessee State Route 55 further crisscross the town but offer limited redundancy in the road network. Given that Manchester is equidistant to major cities like Chattanooga and Nashville—approximately 65 to 68 miles away—its road network becomes a crucial factor in emergency scenarios. The T-REX framework's ability to account for such intricate road systems becomes even more critical here. Given the limited road network redundancy, quick and accurate traffic simulation during mass evacuations is paramount. Especially in a town like Manchester, which frequently experiences drastic population surges due to large events like Bonnaroo, having a portable and adaptable evacuation framework is invaluable. It allows local authorities to make data-driven decisions, mitigating risks and ensuring a smoother evacuation process should the need arise.

3.4.3 Downtown Nashville Around NFL Stadium

Downtown Nashville, particularly around the NFL Stadium, is another critical site for consideration in emergency evacuation planning.

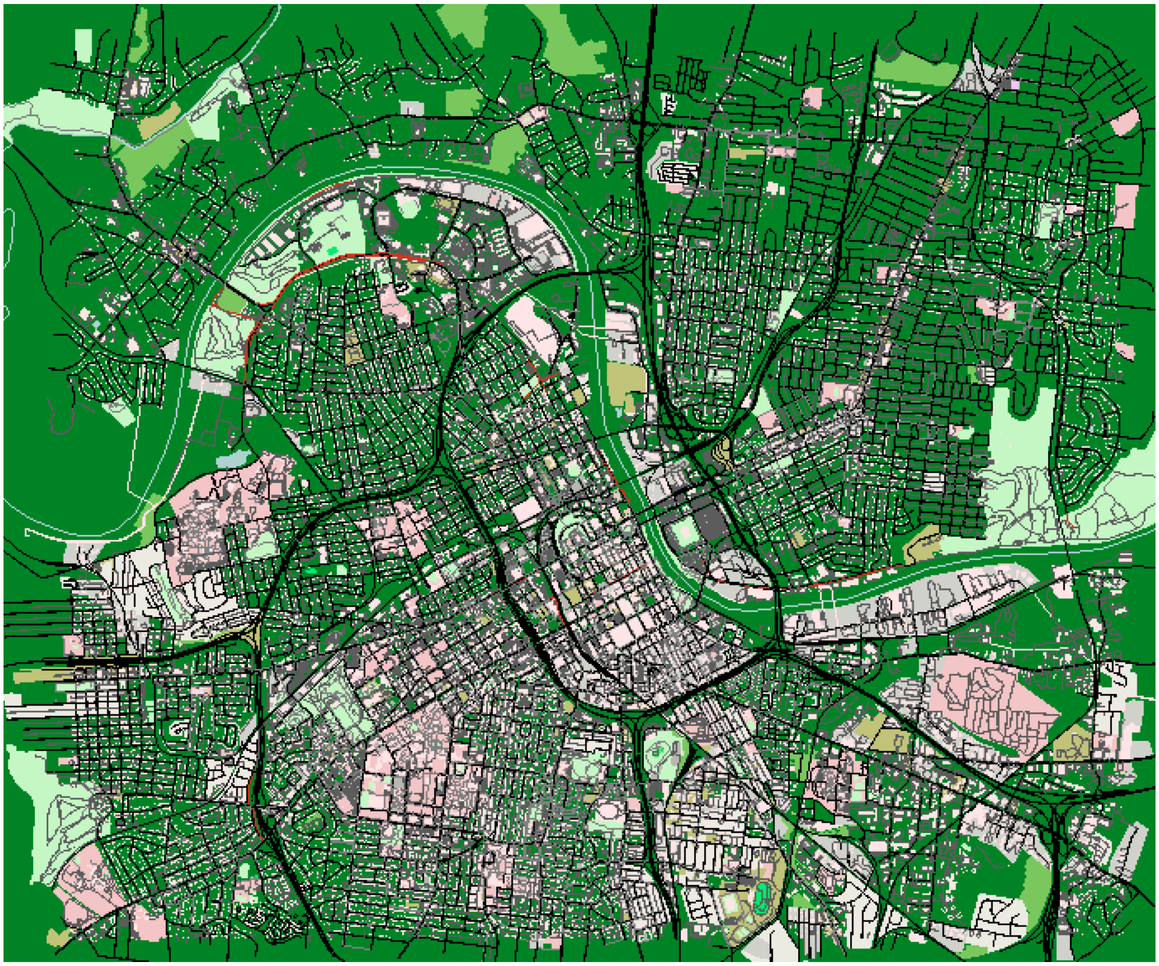


Figure 3-7 Downtown Nashville Study Site in SUMO.

The area is a bustling hub of activity, attracting not only fans on game days but also tourists and locals who visit the nearby entertainment venues. The concentration of people in this relatively confined urban space significantly complicates any emergency response operations, especially evacuations. The existing road network in downtown Nashville, which includes interstates, major arterials, and several smaller streets, faces the challenge of accommodating this heavy, fluctuating pedestrian and vehicular traffic. The CBD area of Downtown Nashville features a grid-like network shape, which is particularly conducive to the implementation of optimization methodology. This network topology aligns well with our analytical approach, especially when investigating optimal loading strategies in later chapters. Consequently, Downtown Nashville serves as an excellent case study for demonstrating the effectiveness and applicability of the T-REX framework in real-world, high-density, urban settings.

3.4.4 Lynchburg, TN and Surrounding Area

Lynchburg, Tennessee, offers a distinct contrast to the larger, more complex urban environments previously discussed. As the home of the Jack Daniel's distillery, it is a tourist magnet despite its small size.

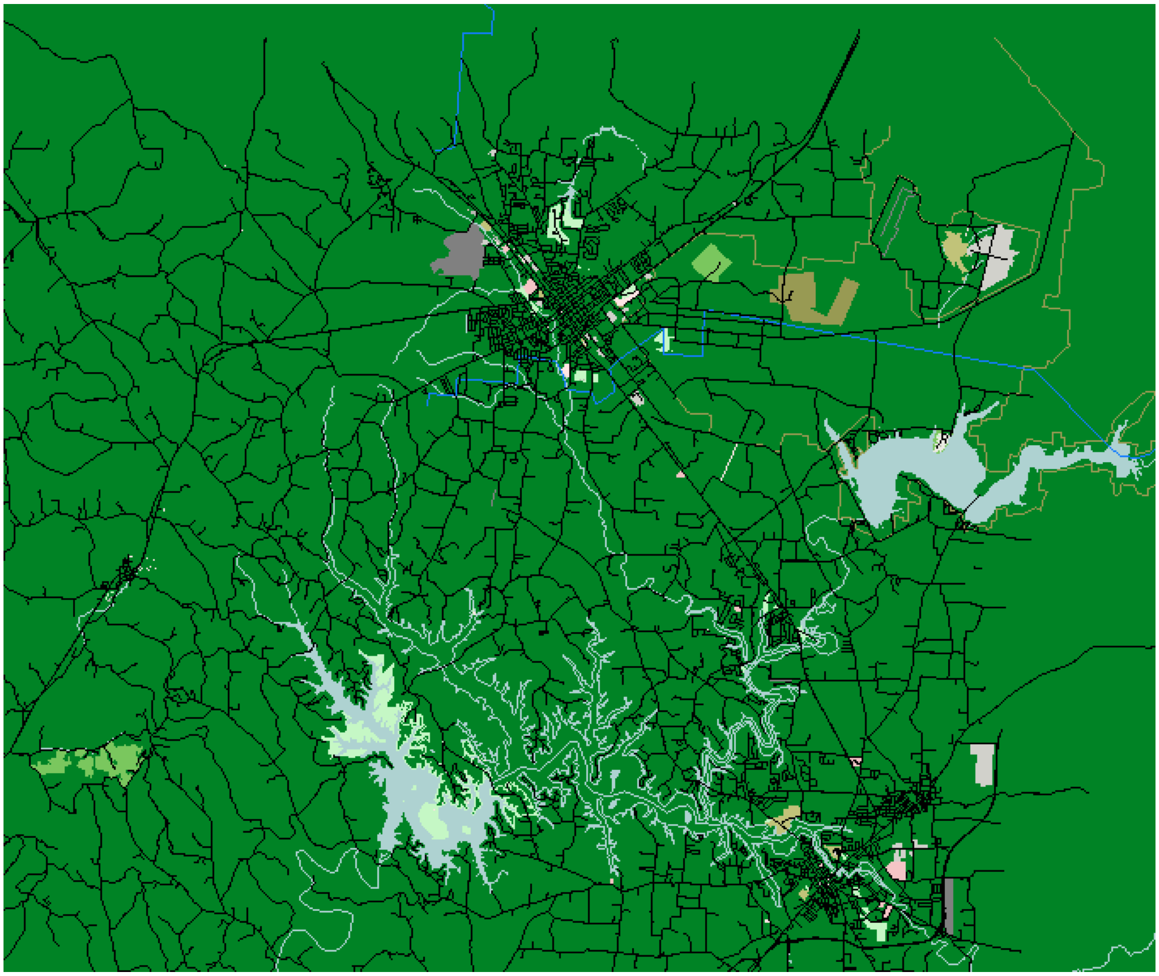


Figure 3-8 Lynchburg, TN Study Site in SUMO.

In Lynchburg, the absence of a bustling traffic pattern or extensive network redundancy underscores the importance of our evacuation scenario study for enhancing the town's resilience. Unlike larger cities where multiple routes may absorb the brunt of an evacuation, Lynchburg's more limited infrastructure means that any bottleneck or inefficiency could have a significant impact. Therefore, applying the T-REX framework to create tailored evacuation plans offers a crucial advantage for a community like Lynchburg, ensuring that it is as prepared as possible for any emergency that may arise.

3.4.5 Wears Valley Area

The Hatcher Mountain/Indigo Lane fire, which ignited on March 30, consumed more than 2,498 acres, offering an area comparable to the previously studied Gatlinburg site. What sets this site apart is the availability of more granular data, which significantly enriches our analysis. Utilizing Sevier County Emergency Management Agency's detailed evacuation plans—publicized through

Twitter—we developed a high-fidelity simulation model. This model integrates high-resolution population data and authentic shelter locations designated by local authorities.

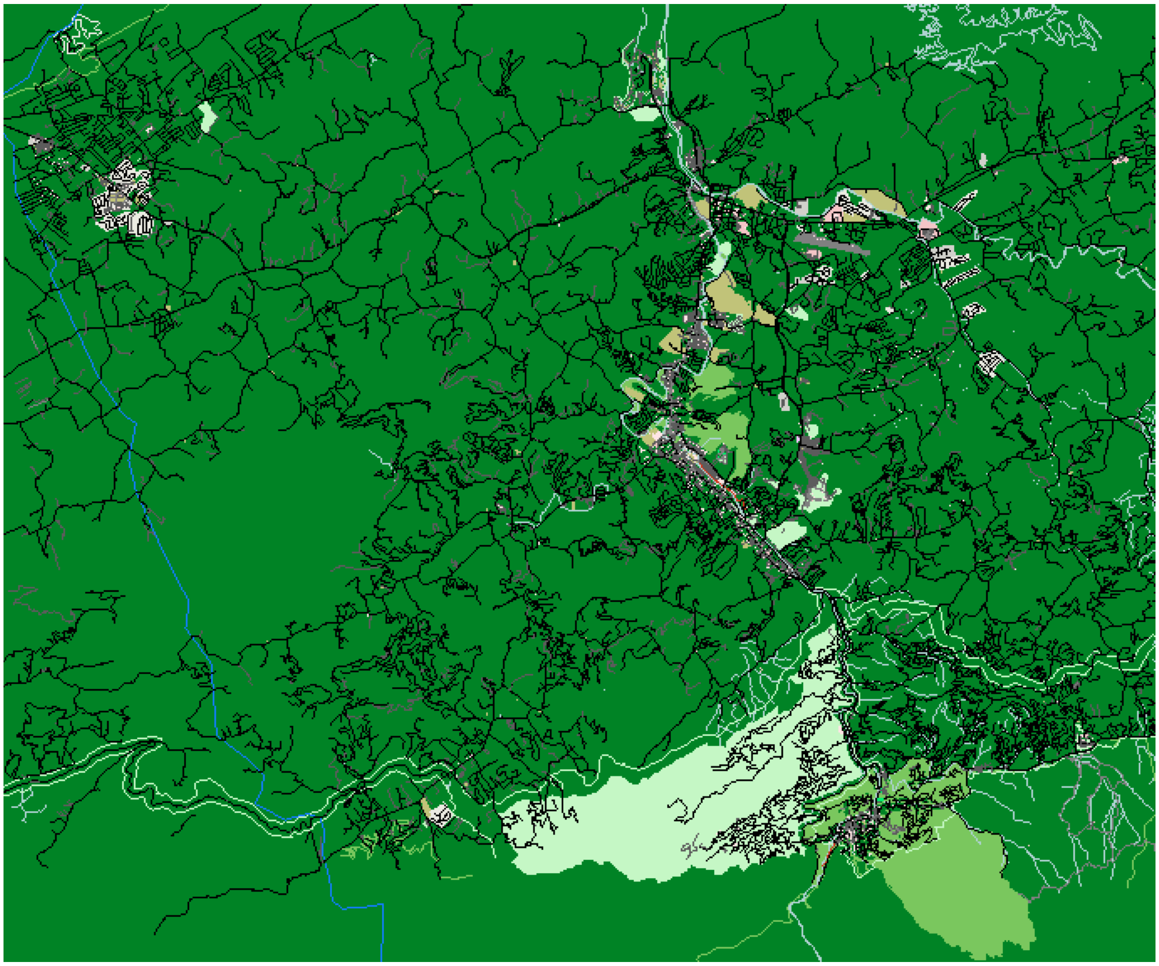


Figure 3-9 Wears Valley Fire, TN Study Site in SUMO.

To capture the complexity and unpredictability of real-world evacuation scenarios, our model incorporates multiple incident variables. These include potential road closures and the varying impact of vehicle types, such as trucks, on traffic flow and congestion. Our analysis aims to identify specific bottlenecks and potential points of failure in the evacuation process, insights we will elaborate on in subsequent chapters.

3.5 T-REX MicroSimulation Engine

In studying real-world network examples, one intriguing observation is the significant impact of loading on overall evacuation performance. "Loading" refers to the initial distribution of vehicles or people within the network prior to the evacuation. Whether it's a city grid, a complex highway system, or a rural road network, the initial distribution can significantly affect the speed and efficiency of an evacuation. In many cases, bottlenecks, delays, and even complete standstills can be attributed not just to the network's layout but also to how the network was "loaded" before the evacuation began.

In response to an emergency, traffic can be loaded onto the network at different rates, which is often achieved through the scheduling of evacuation trips and managing the loading process to optimize the performance of the network. In the extreme case, every evacuee leaving simultaneously, i.e., surge loading, would lead to premature congestion and spillback.

Building on our observations from real-world examples, we devised an abstract grid network using the SUMO simulation platform to delve into the complexities of urgent evacuation scenarios. Our focus is on circumstances where traffic from a Central Business District (CBD) must be swiftly evacuated to peripheral shelters within a matter of hours.

Network Configuration

The network we use is an abstract grid network, which is composed of 400 square cells, laid out in a regular 20 by 20 matrices. The grid structure is reminiscent of a checkerboard, where each cell represents a road segment, also referred to as an `edge', and each point where these edges meet signifies a junction or intersection. The intersections are equally spaced at 40 meters from each other. Each edge in the grid network serves as a bi-directional connection between two junctions, containing two lanes that accommodate traffic in opposite directions. A Central Business District (CBD) is represented by the central 10*10 grid. This area within the grid symbolizes a concentrated commercial and business hub.

All intersections within the network are equipped with traffic lights that operate on a fixed cycle, with a cycle time of 90 seconds. U-turns are disabled at all intersections. The customized network provides high controllability, and every parameter of the network, from the design features such as the number of lanes and road segment lengths, to operational aspects like the timing of traffic signals and speed limits, can be precisely controlled. This granularity in control enables us to adjust the network to reflect a variety of specific traffic scenarios. Later we will show that the monitoring and control measures developed based on this grid network can be transferred to real city networks easily.

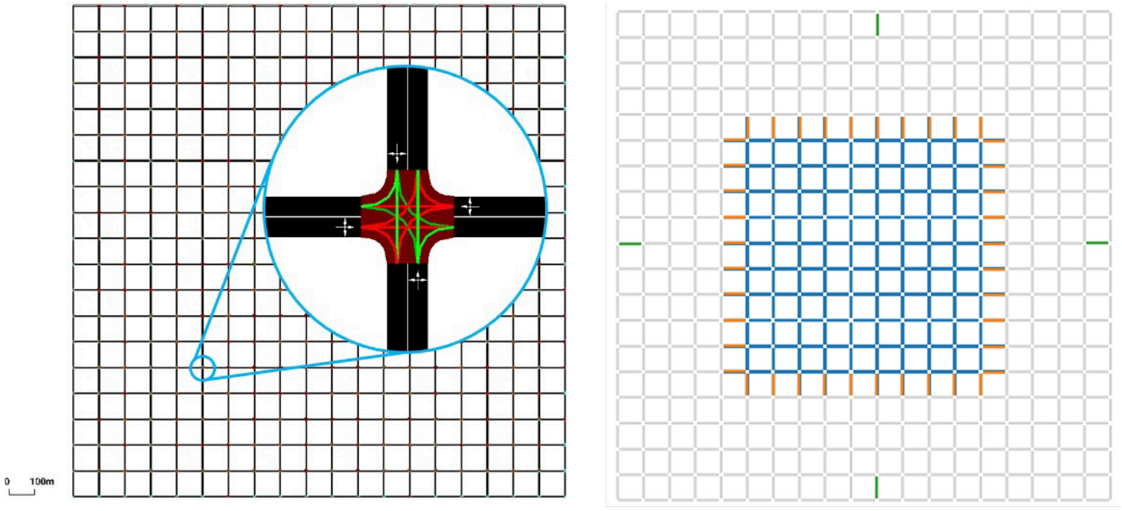


Figure 3-10 Abstract network layout.

Evacuation trip definition

The evacuation process in our grid network commences at time 0, marking the issuance of an evacuation order. As this metaphorical "evacuation clock" starts to tick, every vehicle currently located within the Central Business District (CBD) - the central 10*10 grid - is mandated to evacuate. The orange edges represent exists from the CBD where the evacuation flow must pass. The CBD, under these circumstances, serves as the origin for all evacuation trips. The green edges represent the four designated shelters and serve as the destinations for all evacuation flows. These shelters receive the traffic exiting the CBD. In real-world terms, these green edges could symbolize the entrances to highways or other major exit routes. No traffic exists outside the CBD before the onset of the evacuation; this aspect allows for a clear focus on the evacuation dynamics.

The evacuation demand here is defined as the total number of vehicles to be evacuated from each edge within the CBD. In this paper, the total demand is generated using a Poisson random variable with a mean value of 20, to reflect the inherent uncertainty of real-world evacuations. The loading of evacuees is controlled by the time interval between two successive attempts at vehicle insertion onto a particular edge within the grid. Due to spatial limitations and safety concerns within the network, not all attempts at vehicle insertion may be successful. This could result in delays, known as “insertion delays.” It should be noted that despite these potential delays, no vehicle is discarded from the simulation. Every vehicle is guaranteed eventual insertion into the network. More detailed rules governing vehicle insertion, including handling of insertion delays, will be discussed shortly.

Key simulation settings

In a standard SUMO setup, vehicles that have been waiting for an extended period are automatically teleported to avoid creating a deadlock in the system. We have modified this setting so that no vehicles will be teleported.

Another key variable in the simulation is the level of driver adaptability. The adaptability of drivers can dramatically influence the propagation of congestion and the likelihood of deadlocks. Based on preliminary trials, we set all drivers to be adaptive with a rerouting period of 60 seconds. This decision was informed by observations that non-adaptive drivers contributed to premature deadlock conditions, thereby skewing the simulation results.

To capture a well-rounded view of the evacuation process, data is recorded at multiple granularities. We collect data for each signal phase as well as in 5-minute intervals for aggregate attributes such as space-mean speed, density, and the number of arrivals on each link. This multi-level data collection will allow for a more comprehensive understanding of the evacuation dynamics.

3.6 Congestion/Bottleneck Identification

We further investigated the relationship between the percolation pattern and the evacuation efficiency. Figure 3-11 plots the size of congestion encroachment into CBD versus the evacuation exit flow under different loading rates. Based on those observations, we proposed the following control strategies: i): The percolation-based rule for managing the loading is to ensure that the external, spreading congestion cluster barely reaches the periphery of the CBD. This approach facilitates an equilibrium state that also delivers the highest exiting rate for evacuating traffic; ii) The size of the percolating congestion cluster emanating from a particular shelter can serve as an effective indicator for traffic engineers to assess the immediacy of increasing the service capacity of that shelter or tackling incidents that have reduced its capacity. Given that multiple shelters often operate concurrently, these indicators from various shelters can be leveraged for comparative purposes; and iii) This percolation-based observation approach also gives us a dynamic region that allows loading with maximum efficiency. When the outside congestion invades the predefined CBD, the fixed region for traffic loading is no longer suitable, which should be replaced by a dynamic zone surrounded by outside congestion clusters.

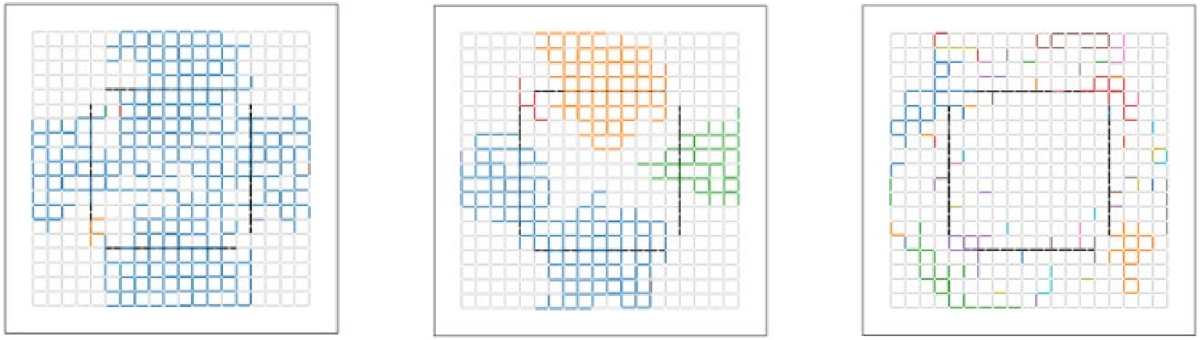


Figure 3-11 Percolating congested clusters with different loading rates: congestion is defined using the critical density of Fundamental Diagram, i.e., $k > k_c$.

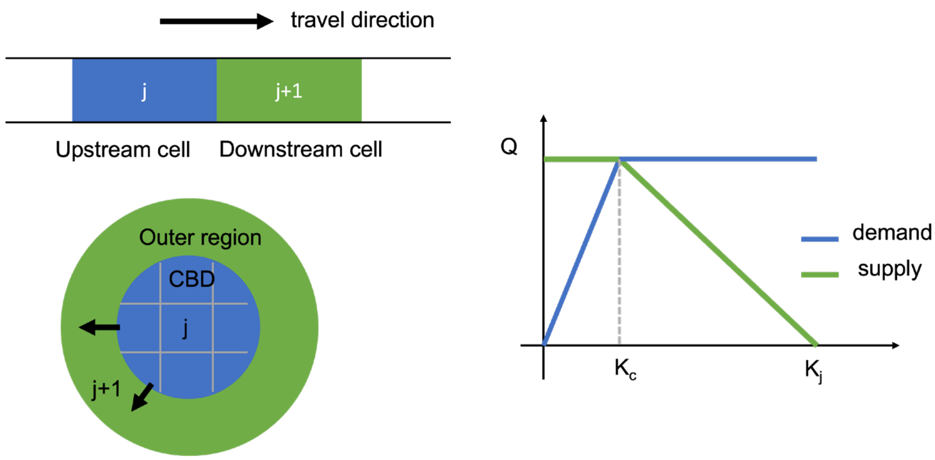


Figure 3-12 Intuition of the control method.

Now we provide some intuition for the percolation-based control strategies. Intuition can be found from the analogy in the 1d evacuation task, e.g., a highway, where the optimal loading rate is very straightforward. As the cell transmission model [10] suggests, the upstream demand (loading) should not exceed the downstream supply; see the supply-demand curve in Figure 3-12. To achieve the maximum evacuating rate, downstream congestion must be cleared.

3.7 Stakeholder Feedback

On May 4th, 2023, UTK research team had a meeting with the Sevier County Emergency Management Agency (EMA). Valuable and constructive advice was shared by the EMA team regarding the impact of the 2022 wildfire in Wears Valley. The collaborative exchange shed light on critical areas for improvement and offered insightful recommendations to enhance emergency preparedness and response.

During this collaborative meeting, we presented our simulation results and demonstrated the utility of the T-REX framework. The Sevier County Emergency Management Agency (EMA) team expressed specific interest in understanding how the T-REX interface could be used to assist in informing locals about evacuation procedures and preparing for potential congestion points. Their practical concerns and feedback will be invaluable as we continue to refine our tools and methodologies, strengthening the applicability of our research in real-world emergency situations.

One of the key takeaways from the discussion was the importance of understanding tourist data, particularly in the Northshille area of Gatlinburg. The EMA stressed the need for the research team to delve deeper into this data to gain a comprehensive understanding of visitor patterns and behaviors during emergencies. This insight would be invaluable in tailoring emergency plans and communication strategies to address the specific needs and challenges faced by tourists in the region.

The EMA's emphasis on road infrastructure and navigation was particularly enlightening. The cut-out roads that hampered the wildfire evacuation highlighted the necessity of finding alternative routes. To address this, the EMA recommended that the research team collaborate with local authorities to develop comprehensive roadmaps for various scenarios, including alternative routes and road closures. Additionally, improving signage and real-time navigation updates during emergencies were suggested as practical solutions to mitigate tourist confusion caused by elevated roadways and flattened navigation.

The EMA's concern regarding Canny Creek, especially during inclement weather, and its lack of recognition by GPS navigation systems, highlighted a significant hazard. To address this, the EMA encouraged the research team to engage with GPS service providers to ensure that such hazards are properly mapped and communicated to users. This collaborative effort could prevent potential accidents and injuries in the future.

Shelter capacity and accessibility were also areas of focus. The EMA acknowledged the challenges faced during the wildfire evacuation, with the Pigeon Forge Community shelter quickly reaching capacity. To address this issue, the EMA suggested exploring the possibility of expanding shelter facilities and identifying suitable health facilities near Wears Valley that could be used for evacuation purposes. Ensuring that shelters can accommodate both permanent and temporary residents was deemed essential.

The EMA's insights into communication and coordination were invaluable. They stressed the importance of collaboration with neighboring communities and jurisdictions to avoid introducing confusion during evacuations. Strategies such as platooning or stop-go traffic management, with a focus on favoring local residents during peak evacuation times, were recommended to alleviate congestion and streamline the evacuation process.

To address the communication challenges experienced during the wildfire, the EMA suggested optimizing the network to prevent overloads and improving wireless emergency alerts and car dial functionalities. Geo-targeting and geo-fencing were proposed to ensure precise information dissemination, while preemptive digital displays and river monitoring systems could keep residents and tourists informed about road conditions in real-time.

The meeting concluded with several innovative ideas for consideration, including initiatives to alleviate congestion on Route 66 and the creation of educational videos to disseminate important data to the public. The EMA also encouraged the research team to explore the possibility of comparing and ranking trouble spots to prioritize improvement efforts effectively.

In summary, the advice and recommendations provided by the Sevier County EMA were instrumental in guiding the UTK research team's efforts to address the challenges posed by the 2022 Wears Valley wildfire. The collaborative exchange highlighted the importance of data analysis, infrastructure improvement, communication enhancement, and effective coordination to ensure the safety and well-being of residents and tourists in the region during emergencies.

Chapter 4 Results and Discussion

4.1 Results

After developing and testing the T-REX framework with four different cases including Gatlinburg fire of 2016, Bonnaroo Music Festival in Manchester, NFL Stadium in Downtown Nashville area, and activities near Jack Daniel's distillery in Lynchburg, we implemented it for the Wears Valley fire that took place in 2022. The daytime and nighttime information from LandScan USA, the transportation network directly ported from OpenStreetMap, and SUMO simulation model, and the evacuation optimization scenarios were all implemented quickly to yield the following results.

4.1.1 Wears Valley (Hatcher Mountain Road / Indigo Lane) Fire

In March 2022, a devastating wildfire struck Wears Valley, causing massive destruction and evacuations of more than 100 buildings in the area; the Hatcher Mountain Road/Indigo Lane Fire was approximately 1,000 acres in size and had affected 35 structures. The UTK research team decided to take this scenario as a case study.

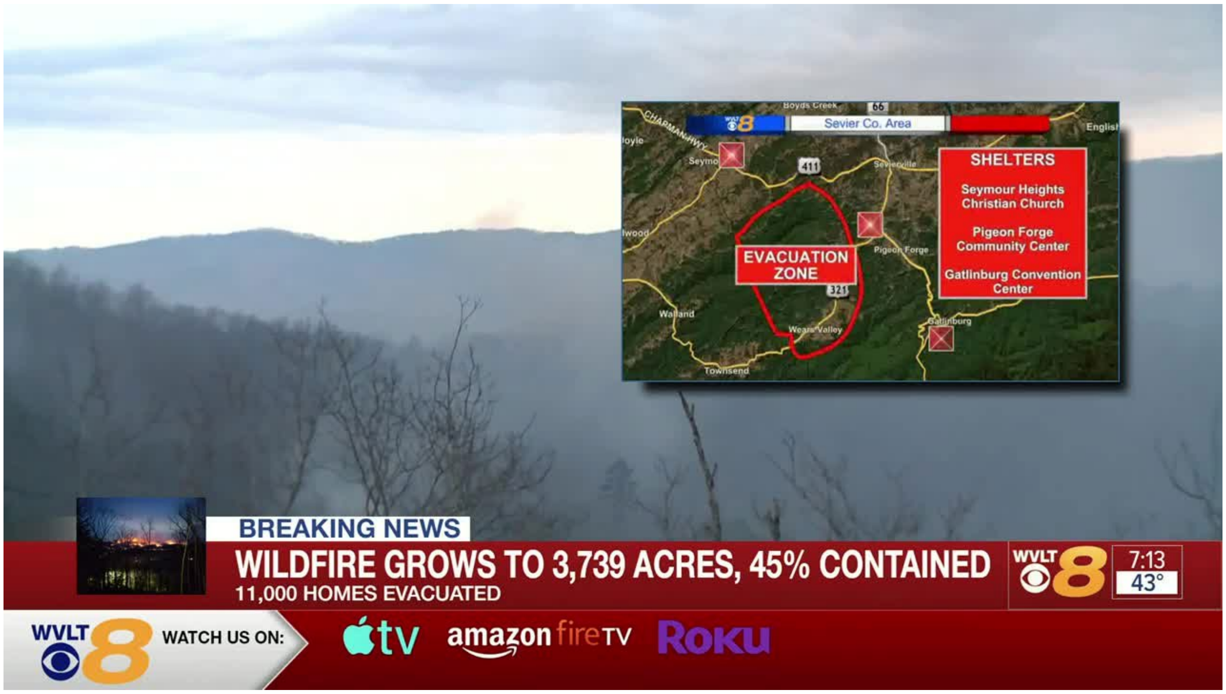


Figure 4-1 News report of Wears Valley Wildfire in March 2022. (Source: https://www.wvlt.tv/2022/03/30/sevier-county-ema-asks-evacuation-wears-valley-area-due-large-brush-fire/)

In our study, we constructed a network in the Simulation of Urban MObility (SUMO) tool, covering both the evacuation area and the fire site as per the information provided by the Sevier County Emergency Management Agency (EMA). This simulation's primary foundation lay in the data sourced from the EMA, ensuring that our modeling was in alignment with actual emergency management parameters.

Our evacuation demand was determined by mapping the LandScan population dataset, focusing specifically on the areas demarcated for evacuation by the EMA. Each evacuee in our simulation was assigned to begin their evacuation from the lane closest to their origin point. To enhance the authenticity and practicality of our simulation, these evacuees were routed towards three pre-designated shelters:

- The Pigeon Forge Community Center situated at 170 Community Center Drive.
- Gatlinburg American Legion Building, located at 1222 E. Parkway in Gatlinburg.
- The Seymour Heights Christian Church, found at 122 Boyd's Creek Highway.

For the purpose of traffic assignment, we employed a shortest-path routing methodology. This approach allowed us to closely analyze the evolving patterns of traffic congestion as the simulation progressed. Notably, this wasn't a one-sided endeavor. After producing our initial findings, we engaged in a feedback loop with the Sevier EMA. This interaction aimed to assess the realism and applicability of our model. Their insights and on-ground experiences were invaluable, as they guided subsequent iterations of our simulation, ensuring that the model was not only theoretically sound but also realistically applicable.

The initial segment of our results presented a comprehensive view of the traffic congestion pattern throughout the entirety of the simulation. We meticulously monitored and tracked the congestion dynamics, offering a holistic overview of the network's response under evacuation conditions. This high-level insight was instrumental in gaining an understanding of the broader traffic flow patterns and potential points of contention.

The analysis was further refined by diving into sub-areas close to two of the designated shelters, allowing for a more granular view of the evolving congestion patterns within those specific regions. The focused scrutiny revealed road-wise congestion patterns in real-time, with Figure 4-3 depicting the tracking for the sub-region near the shelter of Seymour Heights Christian Church and Figure 4-4 showing the patterns near the shelter of Pigeon Forge Community Center. The proximity to these sites exhibited delays and potential bottlenecks during the simulation, which could impede evacuation efficiency. This exploration of localized traffic conditions unveiled critical insights into the specific locations and causes of bottlenecks and suggested potential strategies to alleviate them. The precise identification of these congestion points is vital; they often pose the greatest challenges to efficient evacuation processes and necessitate meticulous attention in the formulation of planning and response strategies.

Figure 4-2 Road congestion pattern tracking for Wears Valley / Indigo Lane Fire.

Figure 4-3 Road-wise congestion pattern tracking for sub-region near shelter of Seymour Heights Christian Church.

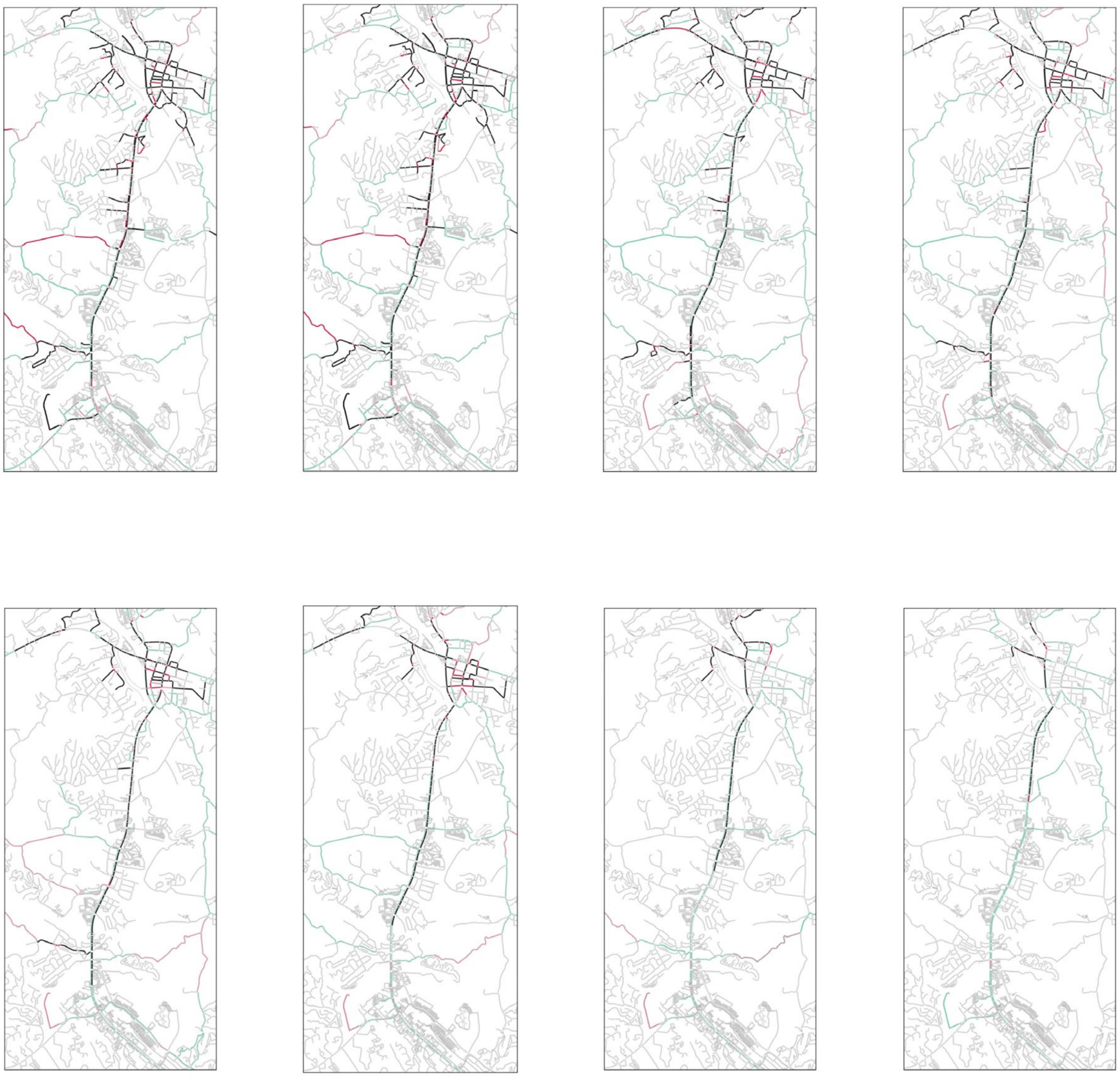


Figure 4-4 Road-wise congestion pattern tracking for sub-region near shelter of Pigeon Forge Community Center.

4.1.2 Optimal loading rate for evacuation

Equilibrium loading

W utilized the 20 by 20 grid-like network of the Central Business District (CBD) area, as previously discussed, to explore optimal loading and its associated strategy. This network, with its distinct structured pattern, served as an exemplary platform for our investigations due to its inherent characteristics conducive to implementing optimization methodologies. By studying this particular network, we were able to discern that an equilibrium loading is intrinsic in grid network structures. To validate our findings and assess their applicability, we then implemented a percolation-based loading strategy in this real-world example, allowing us to observe and analyze its practical implications and efficacy within the specific context of Downtown Nashville.

After 20 rollouts of simulations, we focus on the histories of loading, exiting, and evacuating rates, examining their variations under different desired loading rates.

In these simulations, denotes the number of vehicles inserted per lane per hour within the evacuation zone. This loading rate is implemented by setting a constant time gap (in seconds) between consecutive attempts to insert a vehicle at its trip origin—commonly the departure road in SUMO. The desired loading rate can be directly converted from this time gap using the formula = 3600/(veh/hour/lane).

We also introduce the term evacuating flow (veh/h), which represents the total number of vehicles that have reached their designated shelters within a one-hour timeframe. This is in addition to defining the exiting flow (veh/h), which is the number of vehicles that have left the Central Business District (CBD) or the high-risk area.

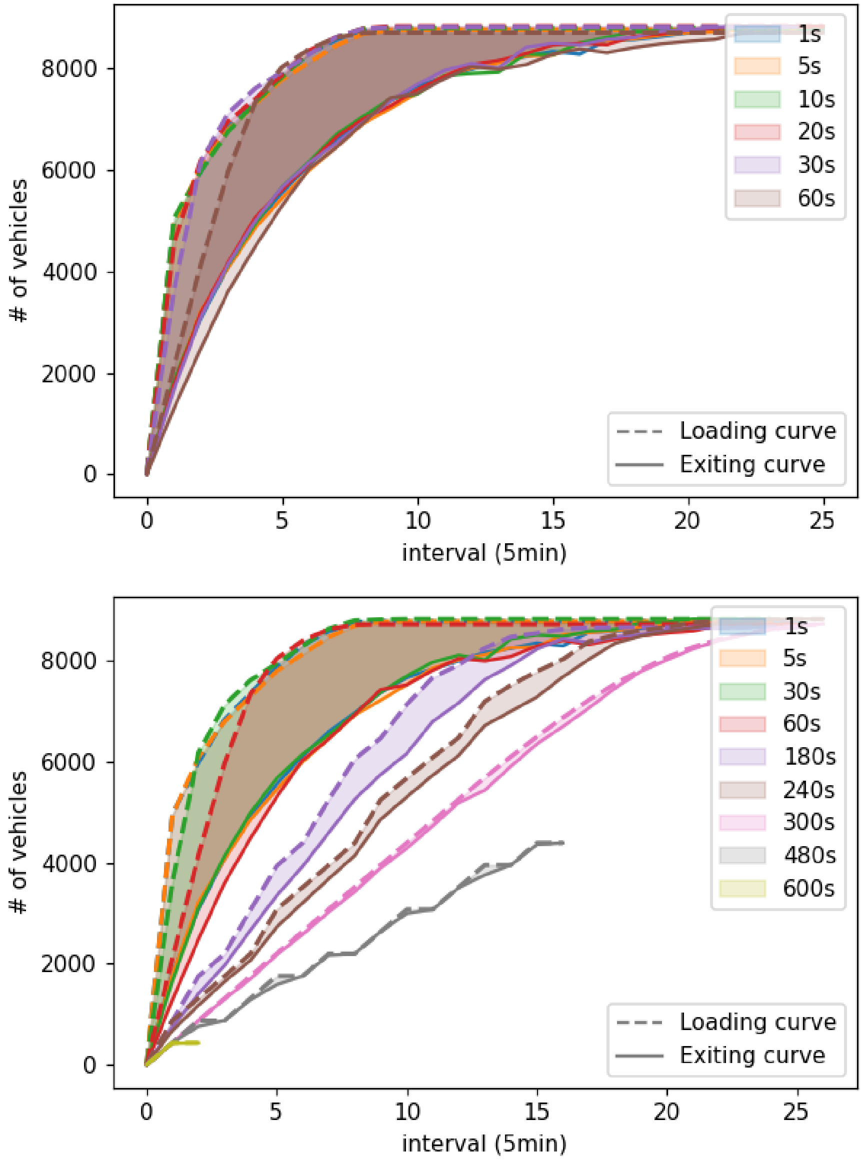


Figure 4-5 Evacuating and CBD exiting rates at different loading rates.

As shown in Figure 4-5, we found that there exists an equilibrium between the loading flow into the CBD and the exiting flow out of the CBD, which simultaneously optimizes evacuation efficiency. Loading can be excessive, over, equilibrium, or under-loaded, with overloading causing widespread jams or even gridlocks.

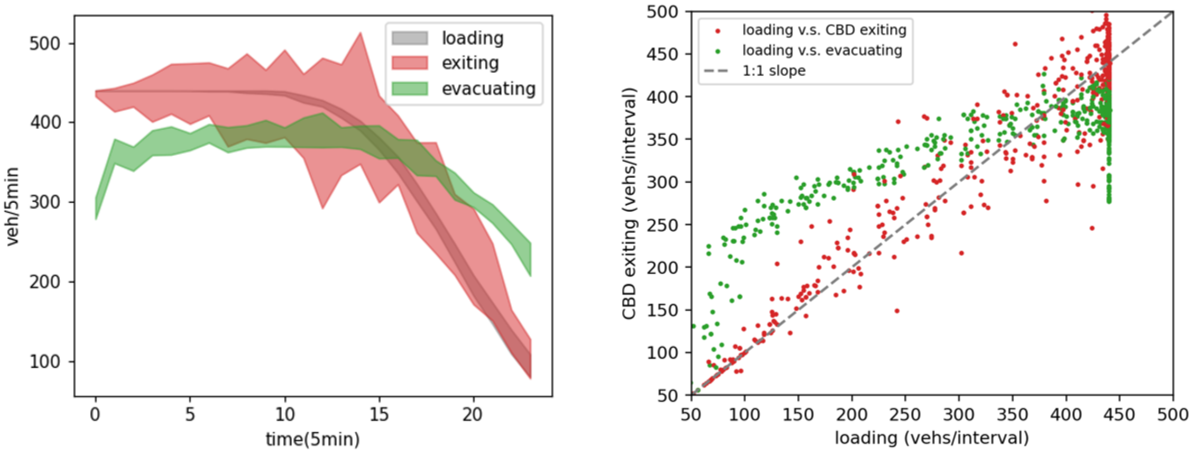


Figure 4-6 Equilibrium between loading and exiting.

In this section, the focus is on elucidating the findings derived from simulations. The histories of loading, exiting, and evacuating are analyzed in the context of varying intended loading rates, representing the number of vehicles incorporated per lane every hour within the evacuation area. This is achieved in the simulation by establishing a consistent interval between consecutive inclusions of a vehicle at its journey's initiation point, typically, the departure route in SUMO.

The concept of 'evacuating flow' is introduced to represent the aggregate number of vehicles that have arrived at their shelter destinations within an hour. In parallel, 'exiting flow' signifies the count of vehicles departing the Central Business District (CBD) or areas identified as high-risk.

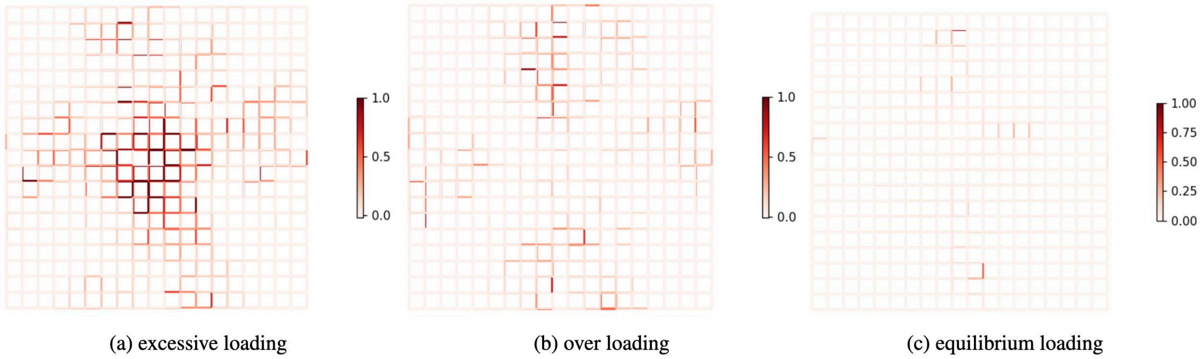
Notably, an equilibrium in the loading and exiting flows is observed, depicted in Figure 4.6, highlighting the equivalent rates of both flows throughout the entire evacuation process. Although these flows demonstrate initial instability with quicker loading and exiting, a balanced state is sustained over a considerable duration, providing substantial insights into the dynamics and equilibrium states of evacuation systems. This balance, and the alignment of scattering points with the x=y line in Figure 4-6, signify a state of equilibrium in the evacuation system, underscoring the vital implications of these observations on evacuation strategies and their executions.

In Figure 4-6, even at equilibrium, the evacuating flow is not strictly equal to the loading or exit flow, which undergoes a varying process that is initially lower but later higher than the loading curve. This is probably due to the limited space of the outer region of the CBD, as well as the limited duration of our simulation. We believe that with a larger outer region and longer simulation time, all three flows will converge to the same equilibrium value.

Issues of overloading

Considering the equilibrium between loading and exiting, we classify evacuation loading into three categories, over-loading, equi-loading, and under-loading, which is greater, equal, and smaller than L^*, respectively. In addition, we believe that there possibly exists a fourth loading state, namely excessive loading, that is when insertion headway is smaller than 60 seconds, forcing a higher but unstable exiting flow, as shown in Figure 4-6. We will shortly show that in this scenario, the network quickly becomes jammed due to congestion from the inner side, rather than the limited capacity of the congested outside region.

Figure 4-7 shows the distribution of waiting time (divided by total time) of all links on the network, under different evacuation loading rates. We observed three different patterns. For the case of excessive loading, we can see that the highest waiting time occurs in the central part of the CBD. In the event of overloading, the longest waiting time is in the shelters. In the equilibrium loading case, the waiting time percentage is negligible. Other metrics such as the queue length are found to similar patterns.



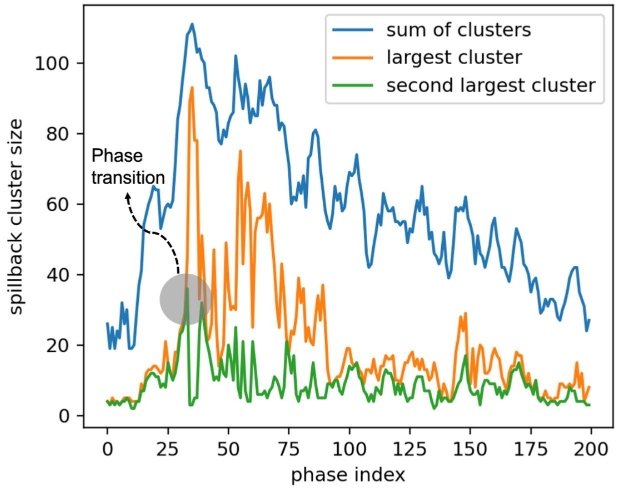
(a) excessive loading (b) over loading (c) equilibrium loading

Figure 4-7 Distribution of waiting time at different loading rates.

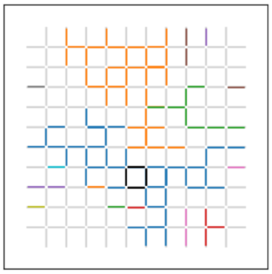
Devastating spillback

Through simulation, we also found that spillover jams propagate extensively in the case of over-loading. Interestingly, connected spillback roads form one or several clusters, which are self-affine and better known as fractals in physics, as shown in Figure 4-8.

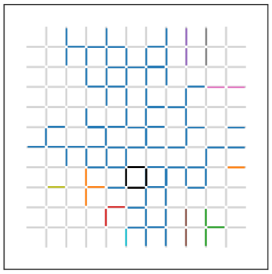
Now we investigate the fractal properties of those spillback jams in over-loading. For example, Figure 4-9 showcases the percolation process of spillback jams of one simulation rollout with $\tau = 120\, s/veh/ln$. According to percolation theory, the phase transition occurs right at the point when the second largest cluster reaches its maximum, as marked in Figure 4-9. After the phase transition, the two largest fractals are aggregated into one large jammed cluster. Also note the dead loop marked in black, which can make the jammed cluster last forever if drivers do not reroute. In this example, thanks to the full driver adaptation used in the simulation rollout, the large jammed cluster dissolves.



(a) percolation process and phase transition



(b) right before phase transition



(c) right after phase transition

Figure 4-8 Phase transition of the spillback jams.

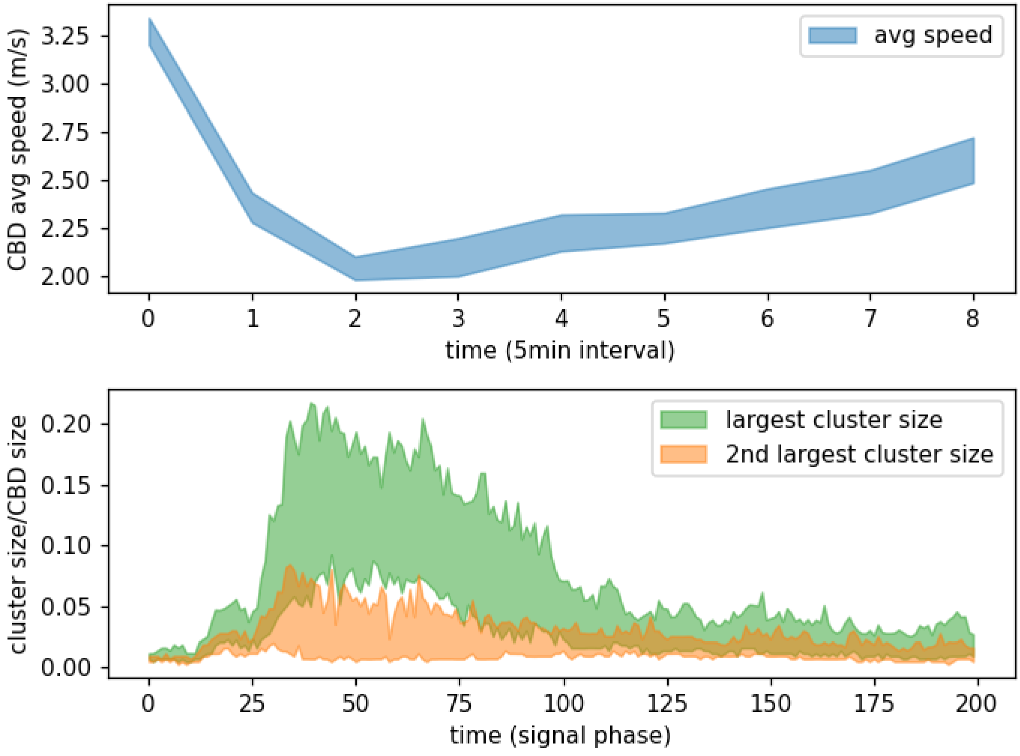


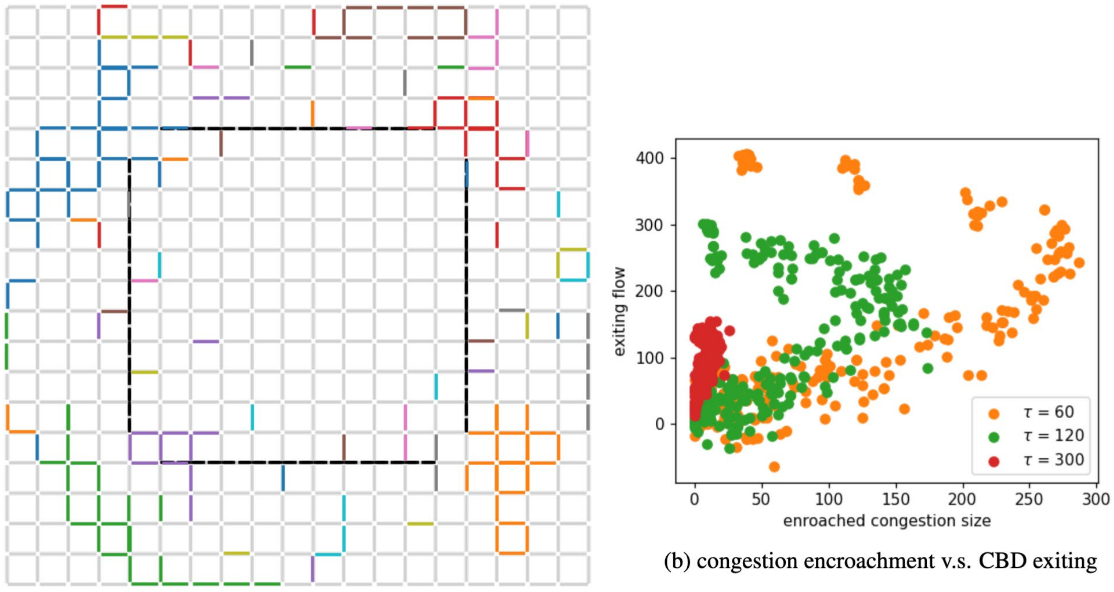
Figure 4-9 Congestion cluster size and average speed of CBD in one simulation rollout.

4.1.3 Optimal loading rate for evacuation

Now we further investigate the relationship between the percolation pattern and the evacuation efficiency. Figure 4-10(a) plots the size of congestion encroachment into CBD versus the evacuation exit flow under different loading rates. The hysteresis in Figure 4-10(b) is due to the loading and unloading phase of the traffic in simulation. We can clearly see that the maximum exit flow occurs when the congestion encroachment is minimal, suggesting that a good control strategy is to prevent the congestion build-up from encroaching into the CBD zone.

Given these insights, we put forward the following percolation-based rules to guide evacuation management:

Rule 1: A primary tenet for managing loading using the percolation approach is to just let the outwardly expanding congestion touch the edge of the CBD. This strategy ushers in a balance that also yields the topmost exit rate for evacuating vehicles. If traffic planners have data on the intended route of evacuating vehicles, they can hone the loading control further. This refinement hinges on initially scrutinizing the congestion pattern in the intended direction and subsequently deciding if that route can bear added traffic.



(a) maximum CBD exiting requires minimum congestion encroachment from the outside

(b) congestion encroachment v.s. CBD exiting

Figure 4-10 Maximum exiting from the CBD danger zone happens at minimum congestion encroachment at the perimeter.

Rule 2: The magnitude of the percolation congestion emanating from specific shelters can be a valuable metric for traffic professionals to gauge the urgency to augment the shelter's service capacity or address issues curtailing its capacity. With several shelters potentially active simultaneously, such metrics from multiple shelters can be juxtaposed for a comparative perspective. This parallel assessment is instrumental in deciding priorities, allocating limited resources, and directing any residual traffic awaiting evacuation.

Rule 3: The percolation layout beyond the CBD offers clues on potential routes for cars and locations for their temporary storage before they finally make their way to shelters. For instance, certain uncongested links in another figure can handle more outbound traffic from the CBD since shelters aren't ready for immediate intake. This lag is evident when noting that peak exit flow and maximum evacuation rates don't synchronize, as seen in yet another figure. Hence, we advocate for optimizing the usage of areas outside the CBD as holding zones for vehicles that have vacated the danger area but remain in queue for evacuation.

Rule 4: This percolation-focused monitoring method also introduces us to a fluid zone conducive to efficient loading. When external congestion spills over into the pre-established CBD, the static loading zone becomes obsolete and should be superseded by a mobile zone encircled by external congestion clusters.

4.1.4 Percolation-based evacuation control for real-world networks

A case study was done on Nashville’s downtown and peripheral areas, where the dashed circle is a CBD zone that needs to be evacuated, and the four highway entrances serve as destinations. The traffic demand is defined as the total number of vehicles to be evacuated from each link within the CBD. The total demand is generated using a Poisson random variable with a mean value of 20, in order to reflect the inherent uncertainty of real-world evacuations.

As traffic managers, when those congestion clusters infiltrate the CBD, such as Shelters 1 and 2 in Figure 4-11**,** the control should be taken to increase the service capacity at 1 and 2, and reroute evacuees to other exits, to improve exiting and evacuating efficiency. Similarly, one can build a spillback cluster to monitor the heavy congestion in the network and concentrate limited resources to resolve those most devastating traffic jams that delay the evacuation.

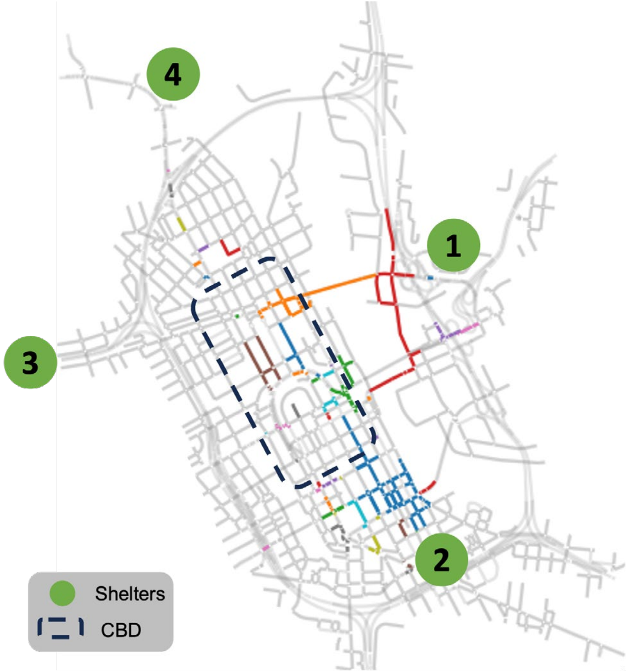


Figure 4-11 Implementing percolation-based evacuation control on city networks: example of Nashville, TN. Those colored clusters are connected and congested (density > critical density).

It should be noted that, real-world scenarios often present bottleneck links where certain roads are prone to congestion. These links can be analogized to bond activation in percolation theory, leading to the aggregation of smaller clusters into larger ones. Identifying the location of such bottleneck links and preventing their bond activation pose intriguing questions worthy of exploration in future research endeavors.

4.2 Discussions

4.2.1 Key Findings

- **Timely Implementation**: The T-REX framework proposed and tested in this study demonstrated that the research team was able to complete the precatory work for utilizing a microscopic simulation software package in a timely fashion. Evacuee information in terms of both daytime and nighttime populations and locations within the evacuation zone were imported from LandScan USA and the transportation network coded directed from OpenStreetMap. It does take some time to assign evacuation destinations for each evacuee and the time they are loaded onto the network based on their locations in the network. Once all input items are ready, the SUMO package can simulate the selected scenario within hours depending on the size of the network, the number of evacuees, and the complexity of the scenario. In general, the modeling process for each scenario can be conducted in a timely fashion.
- **Economic Considerations**: All components selected for implementation in this study, from the population database (LandScan) to the transportation network (OpenStreetMap) to the simulation engine (SUMO), are open, tested, off-the-shelf, and free to the public. This makes it more feasible to implement for local agencies.
- **Flexibility in the Framework**: T-REX is a framework that can be implemented with different component choices. Alternative components such as Streetlight population data, ESRI GIS maps, and VISSIM simulation package or similar can all be used to substitute the open and free components we used in this study. Agencies with models readily developed or preferences in certain databases, could implement T-REX with their own “flavor” with similar success.
- **Results Interpretation**: The simulation of the myriad scenarios at various study sites yielded animation clips, congestion maps, bottleneck locations, traffic control strategies, and traffic operation statistics. These should be used in relative terms in comparison to other similar scenarios at the same sites as opposed to in absolute terms in comparison to actual field evacuation situations. The modeled results could provide insights towards identifying hot spots that may get congested and useful strategies for evacuation management. The experiences and local knowledge from first responders and stakeholders are essential in guiding the interpretations and subsequent policy and operational decisions based on the results.

4.2.2 Challenges and Lessons Learned

- **Participation of Stakeholders**: A significant portion of efforts of this study early on was dedicated to identifying appropriate local agencies and stakeholders, contacting key personnel, and soliciting feedback on respective study sites. The study period coincided with the COVID-19 pandemic period and these jurisdictions are mostly small and isolated communities, the participation and feedback were limited. Sevier Co. EMA, which was quite responsive and sensitive to the subject of emergency evacuation, was an exception.
- **Perception of the Process**: Perhaps due to the publicity, or the potential negative aspects of such, some of the local jurisdictions were not responsive to the repeated attempts to contact by the research team. The perception may be that a simulation tool like T-REX may be used to measure if proper or preferable actions were taken in a evacuation operation in the past. Perhaps, the emphasis should be placed on the fact that T-REX is a tool for planning and evaluating future activities and for help visualizing and preventing future evacuation obstacles.
- **Realism of the Model**: To strengthen the usefulness of a model or simulation package, one typically wants to have realistic feedback for the calibration and validation of the models. Mass evacuation operations tend to be rare and non-recurring events that are difficult to predict, demanding to collect data for in the midst of the pandemonium, and challenging to calibrate subsequently. As such, results from these models and simulations, however sophisticated they might be, should be taken with a grain of salt. Nevertheless, the results of similar scenarios, perhaps with different control strategies or OD assignments, could be compared to afford insights to the decision makers.
- **Expect the Unexpected**: Even with all the modeling and simulation of a wide range of scenarios, the best laid plan of evacuation management could still fall apart due to a vehicular crash and roadway blockage along the main evacuation route. A large tree falling and blocking the evacuation route from Gatlinburg in 2016 was just one of such occurrences. The eventual evacuation operation will unlikely come out exactly like the optimized version in the simulated environment. Therefore, optimization should only be a tool to attain a sense of the order of magnitude of the operations. Multiple unexpected disruptions to the evacuation operation should be expected and factored into the estimation of evacuation duration and resourced needed.
- **Challenges to Implementation**: While the implementation of T-REX is relatively quick and economical, as mentioned previously, there are still technical challenges for smaller jurisdictions to commence the modeling process without the technical personnel, computer hardware, and other enabling resources enjoyed by the larger cities and MPOs. State agencies, such as TDOT, may need to resort to Local Transportation Assistance Program or other similar means to facilitate the implementation.

4.2.3 Implementation Options

- **Technology Transfer through LTAP/UTAP**: A major objective of all of TDOT's research projects is technology transfer or putting the results and findings of the sponsored efforts to practice. In this case, as demonstrated in the case studies, the resultant T-REX framework can indeed be implemented in selected locales. The long-standing Local Transportation Assistance Program as well as the newly established University Transportation Assistance Program are two conduits for such implementations. Through these programs experienced researchers at, for example, the University of Tennessee could following the T-REX workflow to collect necessary data, code the pertinent transportation network, employing off-the-shelf simulation models, and perform evacuation modeling and analysis tasks on computer hardware without extra costs to small local communities.
- **Other Implementations**: In addition to wildfire and other cases studied herein, additional scenarios such as major transportation hazmat spills and mishaps, school and public facility under terror attack, tornado at major sport events, and a number of other hazards can all be evaluated with T-REX type of framework and workflow. It is important that stakeholders and local jurisdictions could participate to provide feedback, to be familiar with the process, and, in general, to provide guidance to the appropriate representation of various characteristics of the population, the network, the hazards, and the countermeasures available to the area.

Chapter 5 Conclusion

This study proposed, implemented, tested, and demonstrated an emergency evacuation modeling framework called T-REX, or Tennessee Rapid Evacuation MicroSimulation. The purpose of the effort is to provide a simple workflow for the implementation in smaller isolated communities or tourist attractions where we often observe 1) captive transportation network options and exit capacity, 2) significant number of visitors unfamiliar with local hazards or evacuation options, and 3) limited resources for planning, modeling, or executing complex evacuation operations.

Five case studies were conducted for Gatlinburg, Manchester, Downtown Nashville, Lynchburg, and Wears Valley area of Tennessee. Using state-of-the-art high-resolution population distribution datasets from ORNL's LandScan USA, employing OpenStreetMap's highway network, and coding everything into the SUMO microsimulation software, this research team modeled and evaluated an array of evacuation scenarios for the five sites. More in depth presentation and discussion of the results of the fifth site at Wears Valley was documented in Chapter 4 because it was the most recent occurrence and because the team was able to obtain detailed feedback from local EMA personnel.

Key findings of the study include 1) the demonstrated timely and rapid implementation of T-REX framework for modeling a handful sites in the state of Tennessee; 2) the economical implementation of the framework because each component was off-the-shelf, tested, and essentially free to use by the public; 3) the framework has the flexibility to be implemented by different agencies with past experience or current preference if different simulation software, population data, or transportation network were to be employed; and 4) the results from T-REX process are to be compared relatively and interpreted carefully by researchers and practitioners to provide insightful recommendations to decision-makers.

There are some challenges and lessons learned in the process of the study primarily related to recruiting the participation of local jurisdictions and soliciting feedback from them. The COVID-19 pandemic that coincided with the study period and the work-from-home aspect also slowed the progress of such. However, towards the later part of the project participation and feedback were provided by a keep stakeholder for the two of the study sites.

Finally, this study also looked into future implementation means for benefiting other sites in and around the State of Tennessee. The funding vehicles of LTAP and UTAP are suitable for engaging university researchers to help local jurisdictions. Perhaps TDOT could consider funding a number of such projects to test implement T-REX in the near future.

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Appendices

A collection of simulated evacuation videos for selected sites and scenarios are provided to TDOT for reference.