Fast Running Application for Evaluating Fire Resilience of Tunnel Systems

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16. Abstract
This report introduces the Thermal Impact Simulator (TIS) programed based on the Confined Discritized Solid Flame (CDSF) model developed during the second through fourth year of the UTC program. It provides a user-friendly interface that allows the engineers to input limited parameters to perform a step-by-step analysis to calculate the thermal impact on tunnel liners resulting from vehicle fires. The analysis is conducted in three steps: (1) tunnel geometry definition, (2) fire definition, and (3) heat flux calculation and visualization. Functionality is included to help the users visually check the tunnel and fire model as needed. The final results can be visualized in the software or exported into an Excel sheet for further analysis. This application is in its first stage and could be further developed. In the next version of this software, a structure performance module will be added to provide a structural safety assessment for the demands considered.

17. Key Words: Thermal Impact Simulator (TIS), Confined Discretized Solid Flame (CDSF) model, thermal impact, tunnel, vehicle fire		18. Distribution Statement No restrictions.	
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List of Abbreviations

TIS: Thermal Impact Simulator

CDSF: Confined Discretized Solid Flame

HRR: Heat Release Rate

HGV: Heavy Goods Vehicle

EXCUTIVE SUMMARY

Throughout the entire UTC-UTI program, there are a number of useful findings and tools developed. However, most of these tools are still in the research stage and are difficult to apply in engineering circumstances due to their complexity in selecting appropriate input parameters and programming-based working space. To increase the impact of this UTC program, an expandable software, Thermal Impact Simulator (TIS), is developed into the first stage (version beta 1.0) to enable sufficient calculation of the thermal impact on the tunnel liner resulting from vehicle fire hazards. This tool is programmed based on the Confined Discretized Solid Flame (CDSF) model developed during the second through fourth year of this program. It provides a user-friendly interface that allows the engineers to input limited parameters to perform a step-by-step analysis. The TIS is still under development to include the damage state assessment module and mitigation optimization module to provide a comprehensive decision-making tool for the engineers to deal with the tunnel structure fire problem.

CHAPTER 1 – Development of TIS

1.1. Introduction

The Thermal Impact Simulator (TIS) is a fast-running application that calculates the thermal impact on infrastructure resulting from vehicle fire hazards. The released beta version (beta 1.0) focuses on the tunnel fire events for both natural and longitudinal ventilation. The tool computes the estimated heat flux on the surface of the tunnel, which can be used as the thermal load for follow-on structural safety analyses.

The TIS tool is based on the Confined Discretized Solid Flame (CDSF) model for both natural and longitudinal ventilated cases. The CDSF model calculates the thermal impact from a vehicle fire in the tunnel by combining both the radiative and convection portions of the event. The flame is modeled as a solid 3D object that radiates emissive power to the ambient environment, while the convective heat flux is generated from the ceiling jet and hot smoke. It is a semi-empirical model developed and calibrated based on both experiments data and Computational Fluid Dynamic (CFD) modeling. The detailed description of the CDSF model can be found in the following publications:

Q. Guo, K.J. Root, A. Carlton, S.E. Quiel, C.J. Naito, Framework for rapid prediction of fire-induced heat flux on concrete tunnel liners with curved ceilings, Fire Safety Journal, 109 (2019) 102866.

Z. Zhu, Q. Guo, S.E. Quiel, C.J. Naito, Rapid Prediction of Fire-Induced Heat Flux on the Liners of Horseshoe and Circular Tunnels with Longitudinal Ventilation at Critical Velocity, Fire Safety Journal, 130 (2022), 103590.

The TIS provides a user-friendly interactive interface, as illustrated in Figure 1, that allows users to define the tunnel dimension and the magnitude of the enclosure and the fire hazard of interest. The analysis is conducted in three steps: (1) tunnel geometry definition, (2) fire definition, and (3) heat flux calculation and visualization. Functionality is included to help the users visually check the tunnel and fire model as needed. The final results can be visualized in the software or exported into an excel sheet for further analysis. In the next version of this software a structure performance module will be added to provide a structural safety assessment for the demands considered.

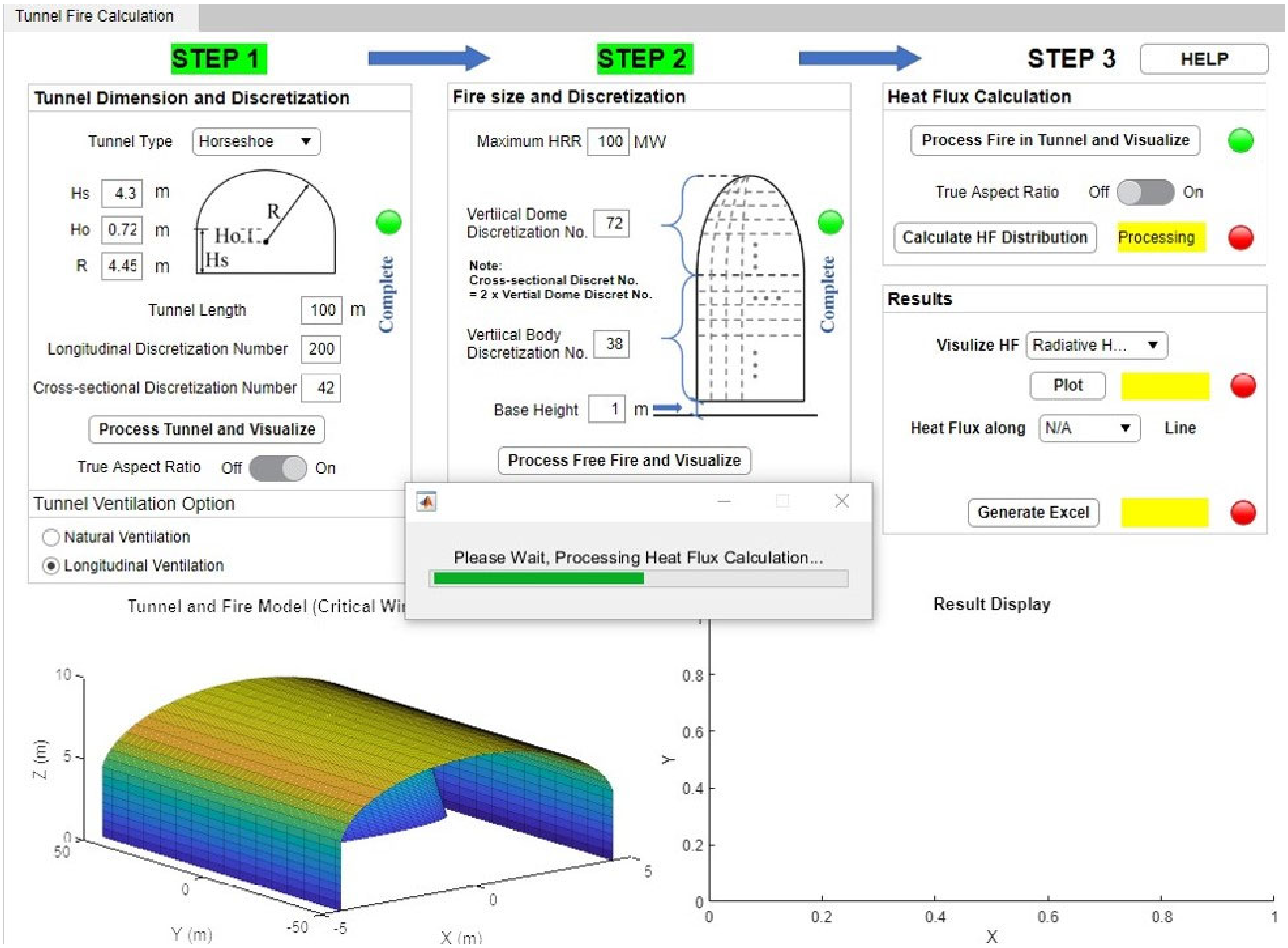


Figure 1: Interactive surface of TIS software

1.2. Brief user manual

Using this software includes three steps: (1) tunnel geometry definition, (2) fire definition, and (3) heat flux calculation and visualization, each step is introduced in the following sections.

1.2.1. Step 1: tunnel geometry definition

The CDSF model is developed for curved ceiling tunnels. The tunnel type considered in this software includes the circular tunnel and house shoe tunnel. By selecting the tunnel type, the corresponding schematic diagram of the tunnel pop-up for users' reference to define the tunnel dimension. Then, the internal surface of the tunnel could be discretized into small rectangular pieces; each piece receives heat flux from the tunnel vehicle fire hazard. Hence, the discretization number could be assigned longitudinally (along the tunnel length) and transversally (along the perimeter of the cross-section). Pressing the "Process Tunnel and Visualize" could construct the target tunnel model, which is then presented for a quick check. The tunnel ventilation provides the options to consider the natural and longitudinal ventilation cases once the vehicle fire hazard occurs. They correspond to whether the jet fans are installed or not. To note, once the longitudinal ventilation is considered, the ventilation speed is default set as the critical velocity, which could prevent the back laying of the smoke to the upstream of the fire.

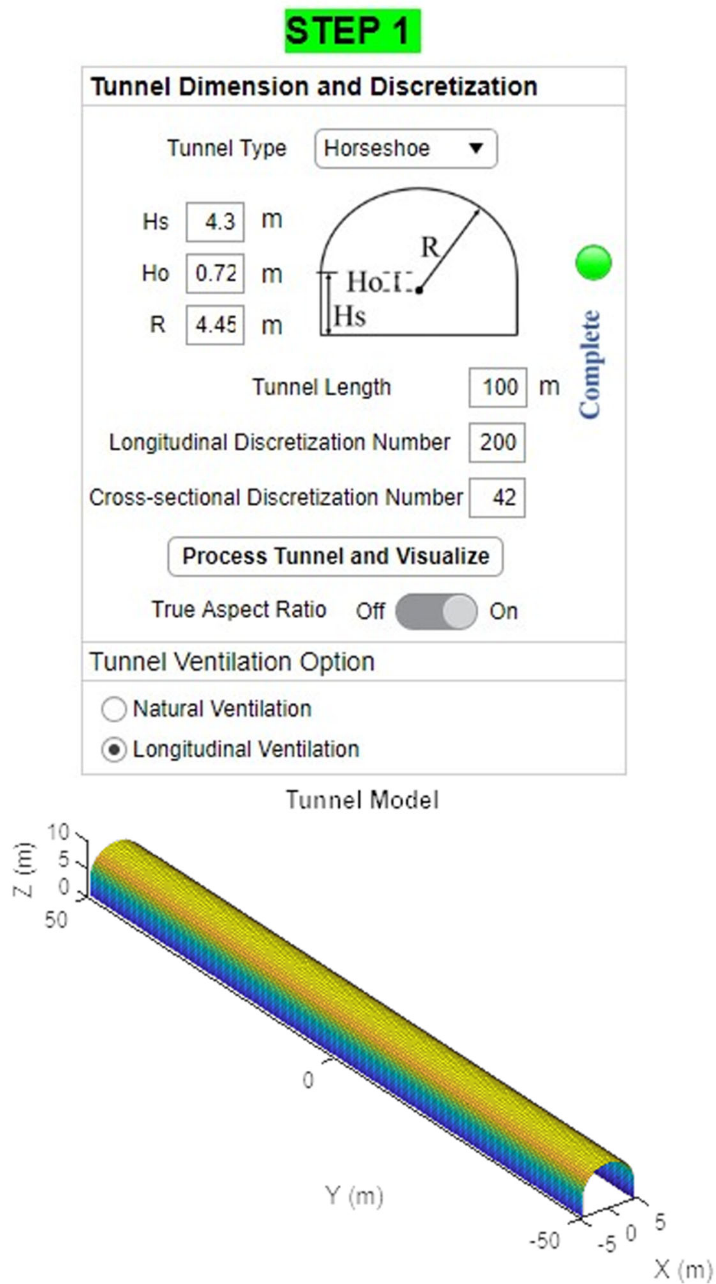


Figure 2: Step 1: tunnel dimension and discretization

1.2.2. Step 2: Fire hazard definition

The second step is setting up the vehicle fire hazard of interest. The intensity of the vehicle fire is represented by the maximum heat release rate (HRR). The base height accounts for the starting vertical location of the fire. Per the CDSF model, the fire is modeled with an elliptical cylinder and an elliptical dome. The vertical dome discretization and body discretization numbers control the discretization of the surface of the fire model. Then, the fire model could be processed and visualized, as shown in Figure 3. Note that the fire model presented here is not confined due to the enclosure of the tunnel.

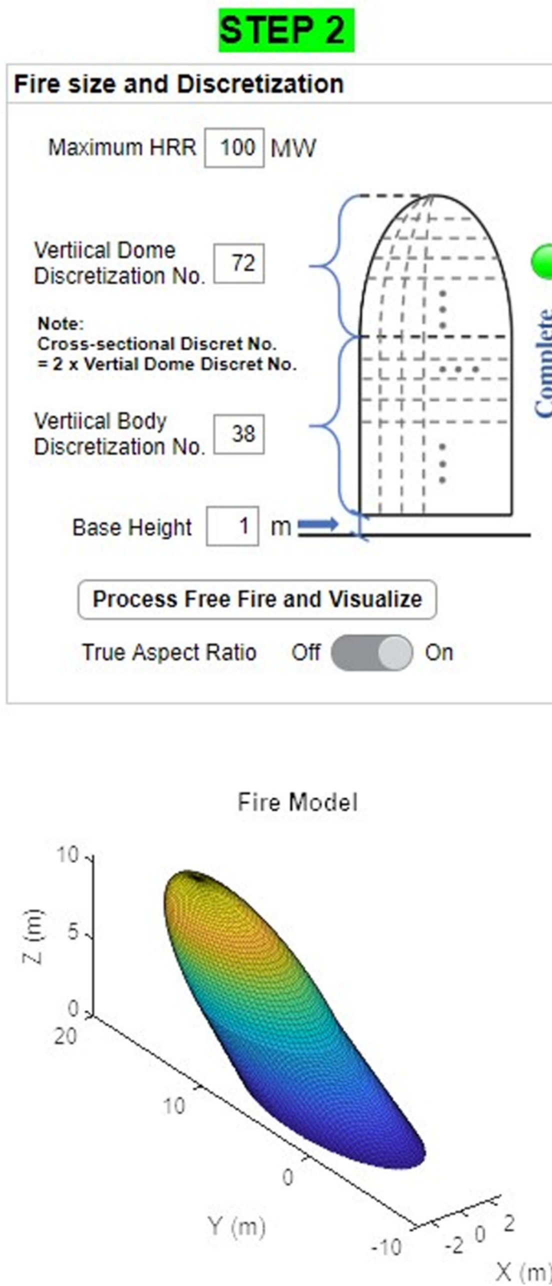


Figure 3: Step 2: Vehicle fire hazard definition

1.2.3. Step 3: Heat flux calculation and results present

The fire is confined in the tunnel geometry, as illustrated in Figure 1. The thermal impact can be calculated with the “Calculate HF Distribution” button on the tool. Once the calculation process is done, the “Complete!” notification activates and the icon at the right-hand side turns green. The distribution of the thermal impact on the concrete tunnel liner can be presented as radiative heat flux, convective heat flux, or total heat flux using the pull down menu. The heat flux distribution is illustrated in Figure 4.

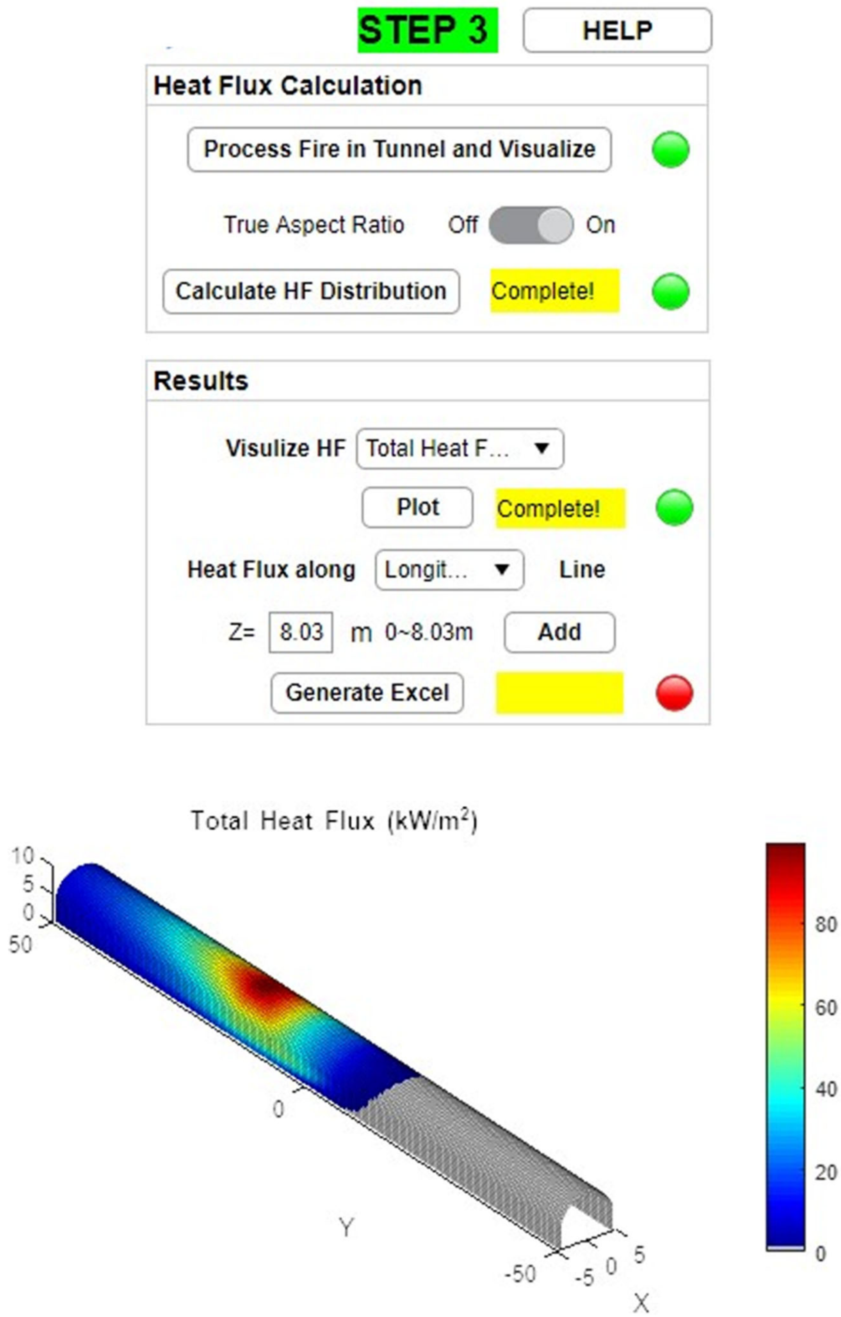


Figure 4: Step 3: Heat flux calculation and results

The heat flux can also be presented at discrete longitudinal or transverse locations, as illustrated in Figure 5. The basic information of the simulation and the results can be exported into the Excel file for further analysis, as shown in Figure 6. These results can be used to evaluate the thermal impact on the interior tunnel surface finish, the tunnel liner structure, and non-structural elements within the tunnel such as false ceiling panels, mechanical conduits, or other fixtures.

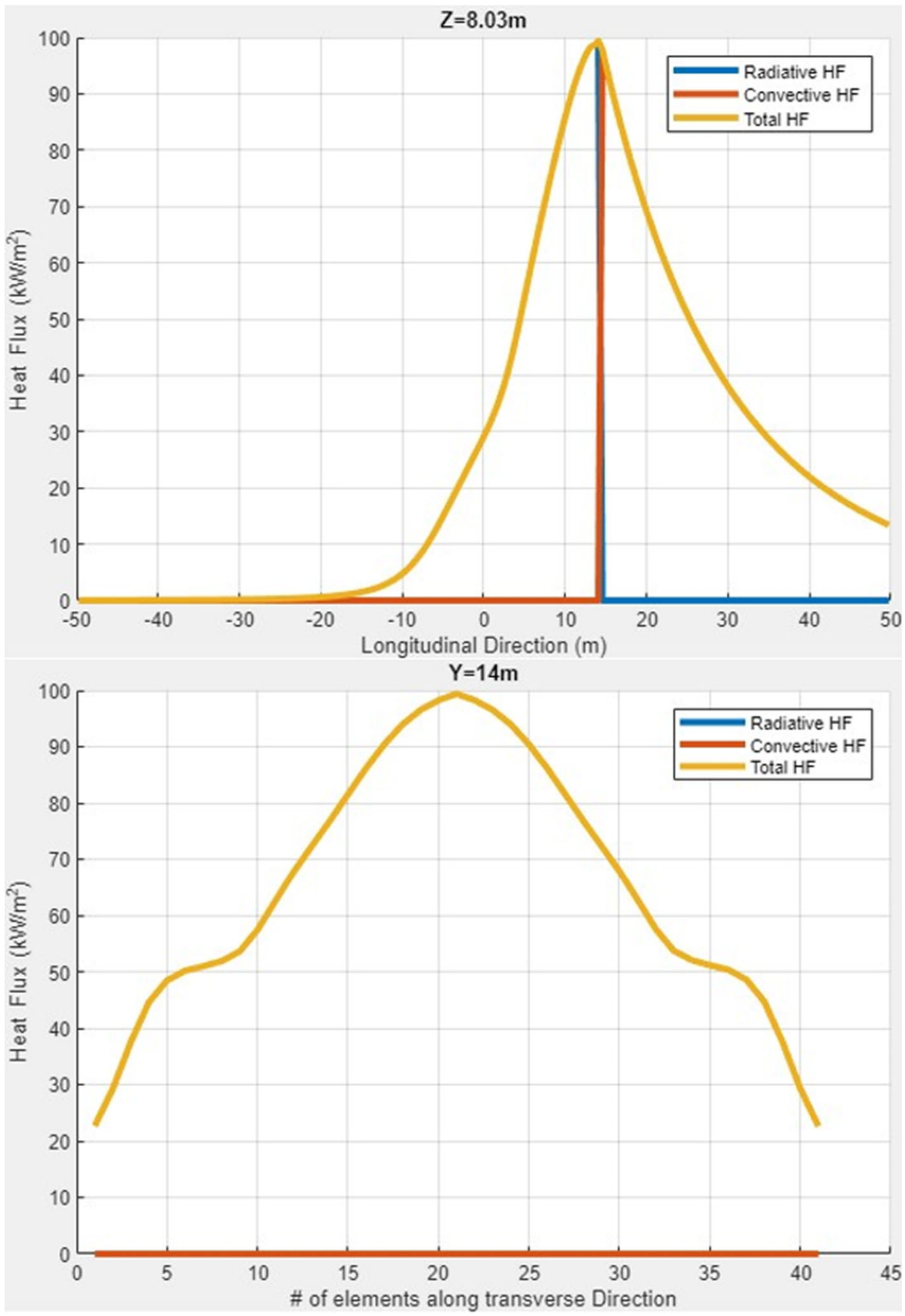


Figure 5: Step 3: Heat flux along the longitudinal or transversal direction of the tunnel

Tunnel Type	Horseshoe
Height(m)	8.03
Length(m)	100
Longitudinal Mesh Number	200
Radius Mesh Number	42
Maximum HRR (MW)	100
Base Height (m)	1
Dome Mesh Number	72
Body Mesh Number	38
Ventilation Condition	Longitudinal Ventilation
Critical Velocity (m/s)	2.979709376

	L122	L123	L124	L125	L126	L127
T1	22.64	22.64	22.64	22.64	22.64	22.64
T2	29.26	29.26	29.26	29.26	29.26	29.26
T3	37.58	37.58	37.58	37.58	37.58	37.58
T4	44.61	44.61	44.61	44.61	44.61	44.61
T5	48.48	48.48	48.48	48.48	48.48	48.48
T6	50.17	50.17	50.17	50.17	50.17	50.17
T7	50.95	50.95	50.95	50.95	50.95	50.95
T8	51.87	51.87	51.87	51.87	51.87	51.87
T9	53.53	53.53	53.53	53.53	53.53	53.53
T10	57.42	57.42	57.42	57.42	57.42	57.42
T11	62.63	62.63	62.63	62.63	62.63	62.63
T12	67.78	67.78	67.78	67.78	67.78	67.78

Maximum Radiative Heat Flux (kW/m^2)	99.38299
Maximum Convetive Heat Flux (kW/m^2)	97.77633
Maximum Total Heat Flux (kW/m^2)	99.38299
Longitudinal location of the Maximum total HF	14.32392

Basic Information	Radiative Heat Flux	Convective Heat Flux	**Total Heat Flux**	Result Summary

Figure 6: Export data to Excel sheet

1.3 Published studies using this software

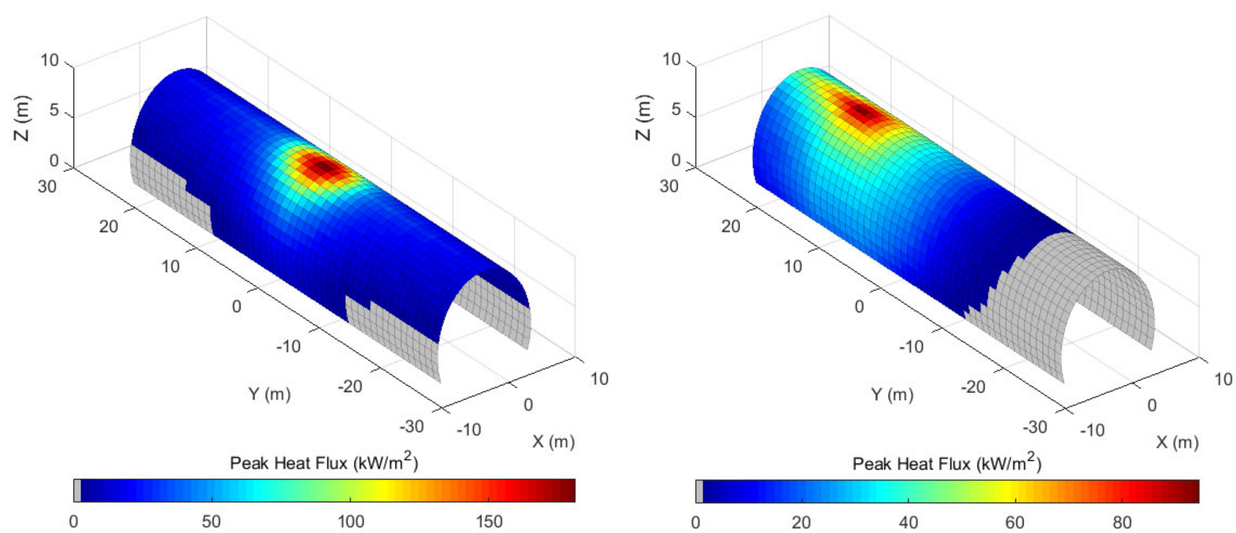
The following studies that implement this software tool for tunnel fire resilience assessment have been published or are being prepared for publication in major technical journals:

Journal: Tunnelling and Underground Space Technology, Vol. 130, No. 104729 (published in 2022)

Title: Performance-Based Evaluation of Exposed Electrical Conduit for Severe Fires in Roadway Tunnels

Authors: Zheda Zhu, Spencer E. Quiel, Clay J. Naito

Abstract: This paper numerically investigates the thermal impact of vehicle fire hazards on exposed electrical conduits in roadway tunnels. By modeling the fire and subsequent heat transfer to the conduit, the analysis results provide performance-based design guidance for allowable temperature increases before the conduit and its contents fail. The computationally efficient Confined Discretized Solid Flame (CDSF) model (previously developed by the authors) is used to calculate the heat flux imparted to the tunnel conduit from the enclosed fire. A simplified finite element model is used to calculate the subsequent thermal response of the conduit piping. Envelopes of conduit temperature increase, as well as exposure duration, are developed for a range of vehicle fire intensities that are enclosed in two- and three-lane circular tunnels. By accounting for overall traffic volume and truck traffic percentage, the limiting criteria for conduit temperature increase during standard experimental testing can be associated with a return period or a probability of exceeding an expected temperature. Sensitivity analyses are performed to examine the influence of conduit size and material, conduit location, tunnel ventilation conditions, average annual daily traffic, and traffic composition.



(a) Natural ventilation (b) Longitudinal ventilation

Figure 7: Illustrative examples of total heat flux from the CDSF model for a 100 MW fire within a 3-lane circular tunnel cross-section

Journal: Resilient Cities and Structures, Vol. 2, No. 3, pp. 1-18 (published in 2023)

Title: Performance-Based Evaluation of Exposed Electrical Conduit for Severe Fires in Roadway Tunnels

Authors: Zheda Zhu, Aerik Carlton, Spencer E. Quiel, Clay J. Naito

Abstract: A framework is presented to quantify the objective-level resilience of reinforced concrete liners of circular tunnels when exposed to enclosed vehicle fire hazards. By assessing the loss of functionality due to fire-induced damage, the framework enables a decision-basis evaluation of the efficiency of various fire mitigation methods for specific tunnel conditions. In this study, the fire-induced damage of concrete tunnel liners due to strength loss and spalling is stochastically simulated and classified based on typical post-fire repair procedures and damage evaluation. The resilience assessment is conducted using Monte Carlo Simulation in combination with a fast-running tool for calculating the thermal impact from vehicle fires on the inside surface of the tunnel liner (developed by the authors in previous work). The proposed approach accounts for uncertainties associated with both the vehicle fire (particularly the combustion energy) and the tunnel conditions (i.e., geometry, dimensions, and the presence of longitudinal ventilation and/or fixed fire-fighting systems (FFFS)). A parametric case study is used to quantitatively demonstrate the effectiveness of FFFS for reducing post-fire losses of tunnel functionality. Other parameters such as tunnel dimensions, traffic restrictions for vehicles with heavy fire hazard risk, and installation or upgrade of the tunnel ventilation system show somewhat less effectiveness for reducing fire-induced damage.

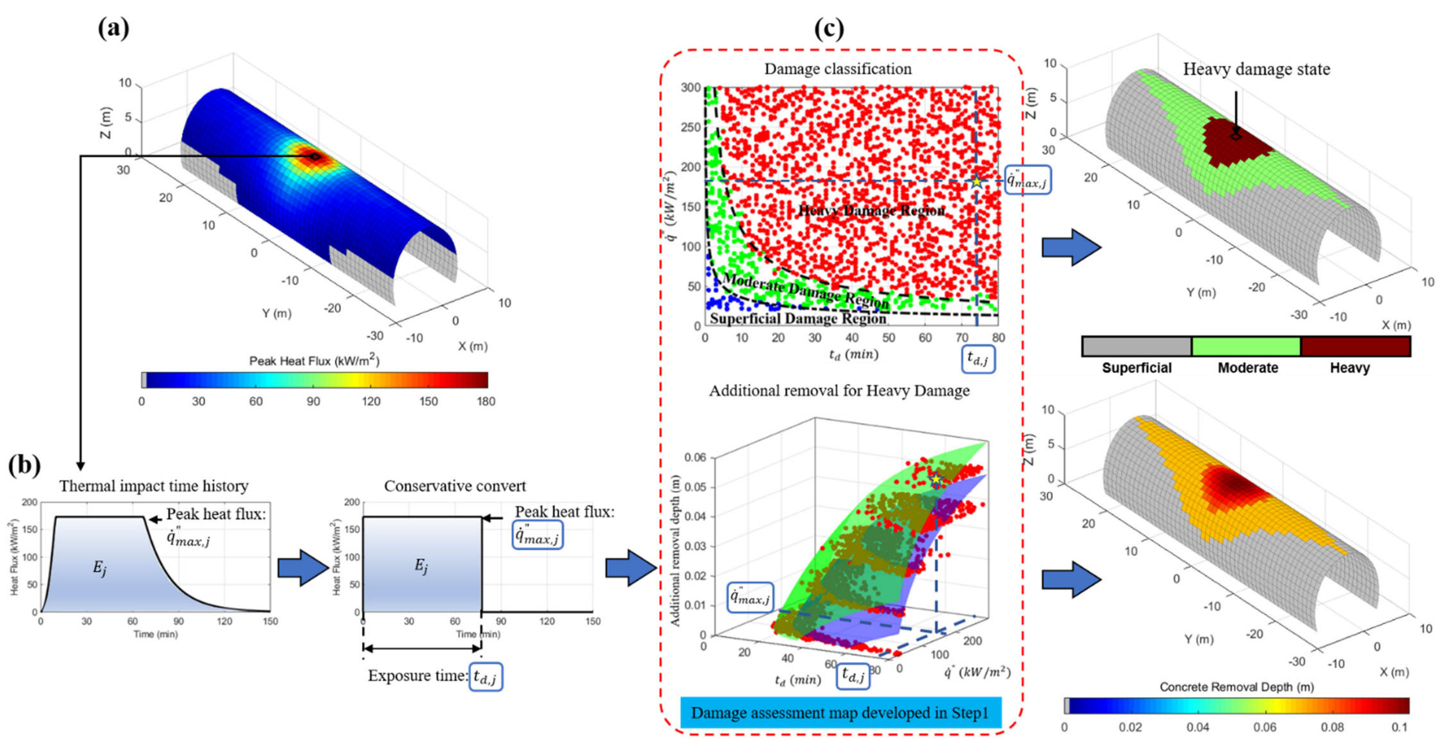


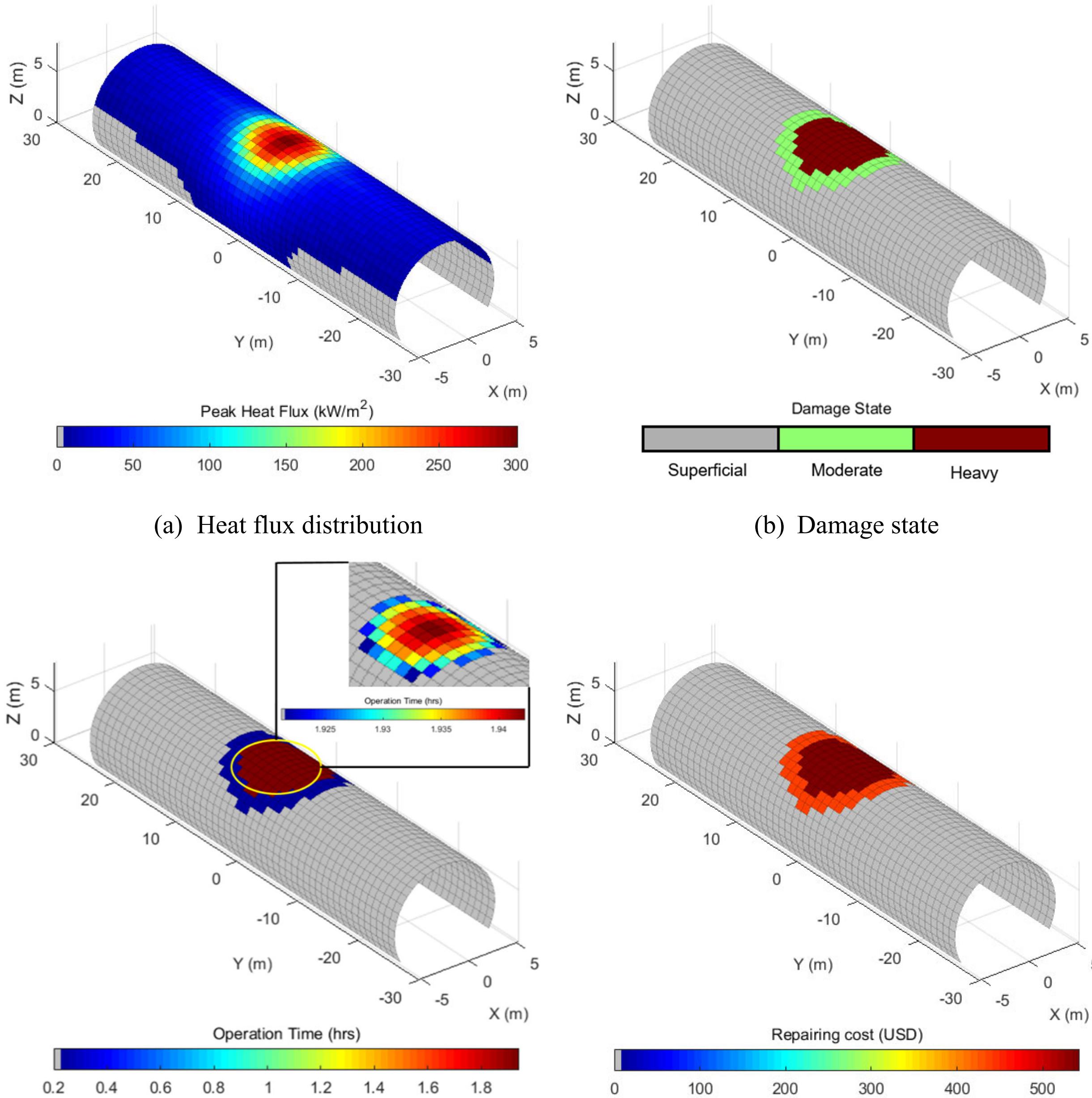
Figure 8: Illustration of concrete liner damage assessment from a 100 MW fire in a prototype tunnel with natural ventilation (using the results of CDSF modeling with damage maps).

Journal: Tunnelling and Underground Space Technology (in preparation)

Title: Optimized Performance-Based Structural Fire Mitigation Strategies for Roadway Tunnels

Authors: Zheda Zhu, Spencer E. Quiel, Clay J. Naito

Abstract: Several technologies such as forced ventilation, active fire-fighting systems, and passive fire protection systems are used in current practice to mitigate fire-induced structural damage and increase resilience for roadway tunnels. Decisions about the cost-benefit of each strategy are often based on a tunnel's geometry, traffic load, and repairability; however, performance-based tools can be used to account for the comparative impact of each strategy on reducing post-fire downtime and cost. This paper outlines a new decision-making approach to optimize fire mitigation strategies for roadway tunnels by minimizing the initial investment and life cycle costs and maximizing the protection efficiency. First, a concrete liner damage assessment tool is developed that accounts for the use or non-use of passive fire protection and the realistic uncertainties in the thermal properties of the materials used. Second, the investment, as well as the economic loss due to stochastic vehicle fire hazards, are quantified for a single mitigation strategy or a combination of strategies. The economic loss includes the direct repair cost and the functionality loss due to tunnel closure, which is determined by the extent and severity of concrete liner damage and the corresponding repair procedures. The thermal impact of the fire on the tunnel liner is calculated with the Confined Discretized Solid Flame (CDSF) model, which is computationally efficient and therefore well suited for stochastic analyses that account for additional uncertainties associated with fire intensity, combustion energy, and the effect of active fire mitigation methods such as longitudinal ventilation and Fixed Fire-Fighting System (FFFS). Third, a genetic algorithm is used to perform a multi-objective optimization, resulting in a Pareto front as the reference for the decision-making process. The objectives and constraints of the algorithm can be readily modified based on practical engineering requirements. The proposed approach is then used to evaluate the sensitivity of fire protection selection to tunnel geometry, traffic volume and composition, and detour length during closure.



(a) Heat flux distribution

(b) Damage state

(c) Repair time

(d) Repair cost

Figure 9: Distribution of (a) heat flux (b) damage state (c) repairing time and (d) repairing cost for a naturally ventilated 2-lane circular tunnel with 6mm fire protection board subjected to fire hazard of 100MW

REFERENCES

Q. Guo, K.J. Root, A. Carlton, S.E. Quiel, C.J. Naito, Framework for rapid prediction of fire-induced heat flux on concrete tunnel liners with curved ceilings, Fire Safety Journal, 109 (2019) 102866.

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APPENDIX A – TECHNOLOGY TRANSFER ACTIVITIES

1. Accomplishments

1.1 What was done? What was learned?

A user-friendly application, Thermal Impact Simulator (TIS), is developed to enable the calculation of thermal impact onto the tunnel liner resulting from vehicle fire hazard, based on the Confined Discretized Solid Flame (CDSF) model, which was proposed in the study during the second to fourth year of the UTC program. It helps to avoid the complicated programming process of using the CDSF model and requires limited input parameters that the users can provide. The final results can be visualized in the software or exported into an Excel sheet for further analysis. The TIS is still under development to include the damage state assessment module and mitigation optimization module to provide a comprehensive decision-making tool for the engineers to deal with the tunnel structure fire problem.

1.2 How have the results been disseminated?

The Thermal Impact Simulator (TIS) software package has been shared with practicing engineers at Thorton Tomasetti (in particular, Dr. Kevin Mueller in Chicago, IL and Kyle Root in Philadelphia, PA). Feedback has been informally solicited, and further developments will be made as a result of those discussions. Additional discussions about dissemination of the TIS package have also been conducted with practicing engineers at WSP (in particular, Dr. Ziyan Ouyang in NYC, NY).

2. Participants and Collaborating Organizations

Name: Lehigh University

Location: Bethlehem, PA

Contribution: (1) software development (2) report

3. Outcomes

The Thermal Impact Simulator (TIS) software package was developed.

4. Impacts

Increase the impact of this UTC program: this software decreases the threshold of applying this CDSF model by providing a user-friendly interface. Users could calculate the thermal impact resulting from tunnel vehicle fires by providing minimal inputs.