WUI-NITY 3

Multi-method traffic movement data collection for WUI fire evacuation modelling

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Foreword

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Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

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NFPA's membership totals more than 65,000 individuals around the world.

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Abstract

In recent years, WUI fire evacuation models have started to be developed. Several now exist, although they are primarily research tools unable to be applied in practice. For this step – moving from research to practice – such models need to build their credibility through testing and application. The WUI-NITY tool has been developed over several previously NIST-funded projects. Once this model is suitably tested and deemed usable, it can be adopted to test different application scenarios as part of engineering practice – beyond simply research applications. The testing process is currently underway; however, it is constrained by the current lack of suitable, available data. In particular, there is a clear need for more data regarding traffic movement during emergency response. Data concerning traffic evacuation is rare enough; however, data sets that can be applied at the required degree of granularity for evacuation models such as WUI-NITY are scarce in the scientific literature.

In this project, several activities have been carried out to enhance data availability for WUI fire evacuation models and improve the WUI-NITY capabilities. This includes:

- The development of methodology for traffic evacuation data extraction.
- The analysis of the Caltrans Performance Measurement System (PeMS) to demonstrate the applicability of the methodology for data extraction.
- The public release of two data sets from actual fires, the 2020 Glass fire and the 2020 Silverado Fire. These data sets are published in open access for any interested party (not only for WUI-NITY, but any model developer/user/researcher).
- The exploratory use of Virtual Reality technology to study traffic evacuation movement variables which we cannot systematically investigate from existing databases (e.g., interaction with information provided by variable message signs). The goal is to use this approach to complement other modes of data collection given the implausibility of performing traditional experiments exploring key unknowns.
- An improved integration of a trigger buffer model (k-PERIL) into WUI-NITY which includes an initial integration of stochastic trigger models.
- The enhancement of WUI-NITY tool. Data obtained were used to improve the WUI-NITY representation of the traffic modelling layer.
- The graphical user interface (GUI) of the model was also improved to ensure that WUI-NITY can be used by a wider range of users and to facilitate its application through clarifying its workflow.

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Nomenclature

Quantities

k	density (veh/km/lane or veh/mi/lane)
l	arithmetic average length (m/veh) of all vehicles passing by the detector
o	detector's occupancy
q	flow (veh/h/lane)
Q	efficiency of the transportation system, the mean speed (km/h)
s	distance headway (m)
S	sum of weighted least-squares
v	speed (km/h or mi/h)
VHT	vehicle hours travelled
VMT	vehicle miles travelled
w	weights in the least-square method
φ	ratio of parameter values during evacuation scenarios and routine scenarios (-)

Model parameters

a	parameters of the model in the Highway Capacity Manual (exponent calibration parameter)
a, b, c	parameters of the model by Van Aerde and Rakha
c	parameter of the model by del Castillo and Benítez (kinematic wave speed at jam density (km/h or mi/h))
m	parameters of the model by Cheng et al. (-)
SD	standard deviation
τ	reaction time in the car-following model by Krauß (s)

Subscripts

$\square_b$	quantity $\square$ at the breaking point, where velocity becomes density depended
$\square_c$	quantity $\square$ at peak capacity, critical quantity
$\square_f$	quantity $\square$ in entirely sparse traffic, free-flow situation
$\square_j$	quantity $\square$ in entirely jammed traffic, total congestion

Units

h	hours
km	kilometres
lane	number of lanes
m	metre
mi	miles
pce	passenger car equivalents
veh	number of vehicles

Abbreviations

AI	artificial intelligence
GUI	Graphical user interface
HCM	Highway Capacity Manual
NIST	National Institute of Standards and Technology
OSM	OpenStreetMap
PeMS	Caltrans Performance Measurement System
SUMO	Simulation of Urban Mobility
TDA	Traffic Dynamics Analyser

UI	User interface
V&V	Verification and Validation
VDS	vehicle detector stations
VMS	Variable Message Signs
VR	Virtual reality
WUI	Wildland-Urban Interface

1. Introduction

Previous projects funded by NIST (60NANB20D191, 60NANB16D282, 60NANB18D255) produced an integrated software platform called WUI-NITY (Ronchi et al., 2020; Wahlqvist et al., 2021) that enables the simulation of WUI evacuation scenarios linking three domains: fire spread, pedestrian decisions and movement, and traffic movement. Thus far, macroscopic sub-models have been embedded and the system has been made available for any interested parties. The intention is for access to this model to remain free. The platform enables input from a range of external sources (e.g., FARSITE (Finney, 1998), OpenStreetMap[1], population distribution data sources such as the Gridded Population of the world[2], etc.) and is able to generate outputs on many systems.

In recent years, work has been completed to develop and enhance the embedded macroscopic models within the WUI-NITY platform (using the Unity environment in which it has been developed), integrate the PERIL system (Mitchell, 2019; Mitchell et al., 2023) (a sub-model that generates trigger buffer estimates supporting procedural design), refine and expand the user experience to ensure that the tool can be employed by stakeholders, and develop and conduct a series of verification and validation (V&V) tests for this and other wildfire evacuation models. All of this has been done to expand key functionalities, give the user more confidence in the results produced, and make the model simpler to use.

Any evacuation modelling tool is only as good as the data available to develop, calibrate, and validate it. The limited availability and use of such tools has effectively reduced the demand for such data sets. Now the need is more apparent and, somewhat fortuitously, there are now more means by which such data can be gathered and compiled; both in terms of sources available and techniques that might be applied to capture them.

A clear need for more data regarding traffic movement during emergency response is apparent (Wong et al., 2020). Some data on evacuation rates, departure times (a function of residential response and vehicles entering the traffic system) and behavioural choices has been collected (Toledo et al., 2018; Wong et al., 2022; Zhao et al., 2022) but a limited set of information is available concerning traffic evacuation during wildland-urban interface (WUI) fire events.

There is a lot of knowledge/data from the traffic domain that is unused and unexplored in the fire safety community. This is for several reasons – from the demand for traffic modellers/engineers to work non-emergency planning and a lack of viable traffic evacuation models to host or apply this knowledge. The present work aimed at generating new data sets and better exploit existing databases to facilitate the transition of existing wildfire evacuation models from research to practice. This data will also help establish the connections between wildfire evacuation and adjacent domains (e.g. traffic engineering) and as a result making more evident the applicability of resources within those domains to wildfire simulation.

1.1. Report structure

In this report, we first outline the overall project objectives that focus on providing new traffic evacuation data and enhancing existing functionality of the WUI-NITY tool. We then describe the methodology adopted in WUI-NITY3. Please notice that the name WUI-NITY3 comes from the fact that this is the third project in which the tool WUI-NITY is being developed. To do this, we present a brief overview of the work packages of the project and describe project

[1] https://www.openstreetmap.org/

[2] https://sedac.ciesin.columbia.edu/data/collection/gpw-v4

workflow. This is followed by a description of the methodology adopted for traffic evacuation movement data extraction. This is exemplified through the use of the Caltrans Performance Measurement System (PeMS) database. Two extracted data sets are then presented (the 2020 Glass Fire and the 2020 Silverado Fire). Then, the report is focused on presenting the developments performed with Virtual Reality tools aimed at studying key variables affecting traffic evacuation decisions while on the road. The final part of the report is focused on WUI-NITY model developments and enhancements. This includes the development of better integration of the trigger buffer model k-PERIL (Mitchell, 2019; Mitchell et al., 2023) with WUI-NITY, the use of traffic evacuation data to improve WUI-NITY calibration and the work performed to improve the WUI-NITY graphic user interface (GUI).

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2. Project aim and objectives

In the attempt to identify freely available data sets for V&V, it became clear that there is an overwhelming lack of data on wildfire evacuation for both model development and subsequent V&V applications. These data include actions taken by households across the entire evacuation timeline: including the pre-travel time period (i.e., evacuation rates and departure times) and the travel time period (i.e., routing, destinations, and movement under different conditions, including traffic congestion or presence of smoke). This project focussed on collecting and analysing evacuation data during the *travel time phase of the wildfire evacuation timeline*. Considering the number of evacuation decisions and subsequent behaviours that occur during the travel phase, including mode, destination, and routing choice, this project aimed to examine evacuee traffic movement characteristics, such as speeds and flows of vehicles during wildfire evacuation.

As a first step, data available in freely available state-level traffic databases were explored and the Performance Measurement System (PeMS) made available for download and use by the California Department of Transportation (CalTrans[3]) was identified as a usable database. Data are there collected on an ongoing basis including track traffic speeds, flows, densities and other characteristics on major highways. These data can be extracted and analysed to better understand traffic behaviours and movements for a specific highway or highway segment during a specific period of time. In this case, we were interested in extracting traffic movement data for highways used for evacuation during a wildfire event.

The PeMS is an archived data user service providing over 10 years of data for historical analysis. It integrates a large variety of information from Caltrans and other local agency systems, such as traffic detectors, incidents, lane closures, census traffic counts, vehicle classification, roadway inventory, etc. to provide critical traffic information along major highways, such as speeds, flows, densities, and occupancies in time and along specific road segments.

This Caltrans database was used to: 1) identify key data available and required to simulate traffic evacuation movement; 2) develop a systematic way to extract these data from traffic movement databases, and 3) create a general use methodology for use by other researchers and model developers interested in interrogating traffic movement databases for their evacuation-related projects.

Once the methodology was developed, the Caltrans PeMS database was used to demonstrate the applicability of the methodology for traffic movement data extraction. The Caltrans data set provided a strong foundation for this work, since it archived data collected from a US state (California) that is consistently exposed to several wildfires every year and will likely be subjected to fires in the future. Data of traffic movement from previous fire events/cases available in the Caltrans archives were extracted as a proof-of-concept of the methodology; i.e., that it is able to extract the necessary data for use by researchers and developers for model development and V&V.

In addition, using the methodology described above, this project extracted and reported traffic evacuation data from two wildfire evacuation case studies from PeMS, namely the 202 Glass fire and the 2020 Silverado Fire. The reported data sets are provided in an open access format such that they can be used by other model developers and researchers in the field. The intention

[3] https://dot.ca.gov/programs/traffic-operations/mpr/pems-source

was to provide a platform for the advancement of the WUI-NITY model, but also for the development of any future wildfire evacuation models.

Additionally, during wildfire evacuation, we know from previous events that smoke from wildfires can travel miles ahead of the fire front (Goodrick et al., 2013), potentially obscuring evacuees' visibility on the roads. Additionally, we know that with rapid fire spread, evacuees can be forced to evacuate quickly and in dangerous conditions, such as heavy ember showers or traffic congestion. Data on how these factors influence driving behaviour, and as a consequence evacuation outcomes, is unfortunately scarce, likely due to ethical and methodological limitations in data collection (Intini et al., 2022). Luckily, virtual reality allows for testing of behavioural hypotheses by comparing relative differences in results between safe and controlled conditions and thus offers a complementary tool to existing data collection approaches (Kinateder, Ronchi, Nilsson, et al., 2014). In fact, a first attempt to study individual driving behaviour in virtual reality during wildfire evacuation scenarios was performed at Lund University, in which it was clearly observed that reduced visibility conditions contributed to a decrease in driving speed (Wetterberg et al., 2020). It is currently unclear though how other environment variables (e.g., environmental conditions, traffic information) would affect driving with and without the presence of smoke.

Therefore, this project also investigated the use of virtual reality simulations to study evacuee behaviour under these types of conditions. The goal was to identify and develop likely evacuation scenarios involving environmental conditions from recent fires, create realistic virtual reality simulations of these scenarios, and pilot test these scenarios with a small group of participants.

While these tasks involving the collection and analysis of traffic movement data were being completed, efforts were performed to improve the capabilities and usability of the WUI-NITY model based on the work conducted. This included improvements in the traffic modelling capabilities, better integration with trigger buffer model k-PERIL and Graphic User Interface Enhancements. The intention here was that the model is being made more credible through access to better data, and more viable by making it more accessible to the practitioner.

Overall, the current project addressed the following set of key research objectives by developing a multi-method approach for the extraction and analysis of WUI fire traffic evacuation movement data sets.

- **Methodology for data extraction**: First, key available data concerning traffic movement in evacuation scenarios were identified. Then a methodology for data extraction was developed with the specific aim of using traffic movement data for integrated WUI fire evacuation modelling.
- **Analysis of candidate database:** The data available in the Caltrans Performance Measurement System (PeMS)[4] was used to demonstrate the applicability of the methodology for data extraction.
- **Data Collection:** Next, traffic movement data from two case studies (the 2020 Glass fire and the 2020 Silverado Fire) were extracted and reported. These data sets are published in open access for any interested party (not only for WUI-NITY, but any model developer/user/researcher).
- **Exploratory use of VR:** Virtual reality technology was used to study traffic evacuation movement variables which cannot be systematically investigated from existing

[4] https://pems.dot.ca.gov/

databases (e.g., interaction with traffic information or environmental conditions). The goal was to use this approach to complement other modes of data collection given the implausibility of performing traditional experiments exploring key unknowns.

- **Enhancement of WUI-NITY tool:** Finally, the data obtained in previous tasks were implemented in WUI-NITY. The data collected allowed enhancements in the traffic modelling layer of WUI-NITY – therefore increasing its credibility and the potential for its use by practitioners. The graphical user interface (GUI) of the model was also improved to ensure that this potential for use can be exploited. The GUI was further developed based on a detailed understanding of when/where a practitioner might be active along the design and operational timeline. The integration between k-PERIL and WUI-NITY was also enhanced.

The main outcomes of the project include:

1. Identification of key data available that can be used for the development, calibration, and validation of the traffic evacuation movement component in integrated WUI-fire evacuation models. A methodology for data extraction from traffic movement databases (CalTrans is used as starting point) is developed and a software allowing PeMS data extraction is publicly released for free.
2. Two data sets (2020 Glass Fire and 2020 Silverado Fire) are being published in an open access such that they can be re-used for other research initiatives.
3. Exploratory use of VR for traffic movement to examine factors known to affect performance (traffic interaction with smoke), given the impracticality of examining it in more traditional experimental modes.
4. WUI-NITY being further developed based on new info/data. This involved the enhancement of the model to reflect [1-3 above] and also the evolution of the GUI to ensure practitioners can apply the tool across a range of viable applications.

3. The WUI-NITY3 project structure

In this section the project structure is presented along with the general workflow adopted for the multi-method traffic evacuation data collection approach for wildfire evacuation model.

In the previous NIST-funded projects (Ronchi et al., 2017, 2020, 2021), a platform able to integrate fire, pedestrian and evacuation modelling layers was built. The main aim of the project was to increase knowledge on traffic evacuation during wildfire events. This included developing a methodology to collect and analyse data from traffic movement databases, the exploratory use of VR to investigate traffic movement (e.g., environmental conditions involving fire/smoke and traffic information) in the absence of other viable means, and the enhancement of the tool to facilitate use by practitioners.

The updated WUI-NITY platform was built within a project with the following work package (WP) structure.

WP1. Project management and dissemination: This WP refers to the management of the activities of the project, communications with the panel and the dissemination of the results. The Foundation coordinated a Project Technical Panel comprising key community representatives and subject matter experts.

WP2. Development of a methodology for traffic evacuation movement data extraction. This WP included the identification of the key data needed for the development, calibration, and validation of the traffic movement component of an integrated WUI fire evacuation platform and the modes by which this data can be compiled (such as WUI-NITY). The data under consideration are selected in relation to the type of modelling approach and the scale of the wildfire scenarios. Data identification is followed by a methodology for data extraction from existing databases.

WP3. Extraction of data from a traffic database. A traffic database, the PeMS data source from CalTrans, was used as a proof of concept for the application of the methodology presented in WP2. Testing of the methodology for identifying key data useful for wildfire evacuation development, calibration, and validation is performed and key data are extracted and analysed.

WP4. Open access WUI fire evacuation case studies. Two wildfires were identified, the 2020 Glass Fire and the 2020 Silverado Fire for data analysis. Data were extracted from the database (over time and over highway segments) using the methodology identified in WP2: traffic flow, speed, occupancy/density, etc. were extracted and published. These data are released in an open access format for future use by evacuation modellers and others in the evacuation community.

WP5. Fire/smoke interaction during traffic evacuation movement. This WP includes the development of a virtual reality simulation for driving in a wildfire scenario. Data on how these factors influence driving behaviour is unfortunately scarce, with the only existing study focusing on individual driving behaviour during evacuation (with an absence of any other vehicles on the road) (Wetterberg et al., 2020). The WP identified relevant driving scenarios and developed a study protocol and virtual reality prototype that allows for the systematic manipulation of environmental conditions and measurement of relevant human behaviour (e.g., driving speed, decision making). A pilot study was performed to test the applicability of the VR scenario. The necessary ethics approvals were obtained as the experiments met the requirements of the Common Rule for the Protection of Human Subjects. The data generated can then be used to further develop a full-scale study of driving behaviour using VR.

WP6. WUI-NITY Model Development. This task refined the current model capabilities in light of findings from WP2-5. This included the incorporation of data collected as a basis for the macroscopic representation of traffic evacuation in WUI-NITY. Better integration of k-PERIL in WUI-NITY to assess community vulnerability was performed in order to provide guidance on evacuation planning. In addition, the user access to the model was simplified to ensure that the practitioner (as opposed to the researcher) can access and configure the model and interpret the results produced. This was performed improving the Graphic User Interface of WUI-NITY and clarifying the application workflow.

4. Methodology for traffic evacuation data extraction

The first step towards a methodology for traffic evacuation data extraction is the identification of the key variables available in traffic databases and how they can be used in traffic models. Therefore, a first step of the work has been to identify key variables and review their relationships. As WUI-NITY currently make use of a macroscopic modelling approach, the main focus has been so far on macroscopic relationships. This was followed by an assessment/categorization of the road type under consideration as this is key to understand information provided by traffic databases. Following this work, the methodology for traffic evacuation data extraction is presented, which has been implemented in a tool called the Traffic Data Analyser (TDA).

4.1. Speed-density and flow-density relationships

Macroscopic traffic models employ speed-density relationships (or flow-density relationships) to simulate traffic dynamics. Therefore, the accuracy of macroscopic traffic models depends on the chosen relationship and the related parameters. In this section, different relationships (further called models) are studied. Moreover, values are suggested for the relationships' parameters, depending on the road type. The goal is to provide a basic understanding on the key variables needed in macroscopic models that should be sourced from traffic databases.

Many different relationships (models) have been proposed over the last century. Here, a set of well-known traffic models (See Equation 1 to Equation 8) are presented.

Equation 1 presents the parabolic model by Greenshields (1935), often also referred to as the Lighthill-Whitham-Richards model (Lighthill & Whitham, 1955; Richards, 1956).

$$v = v_f\left(1 - \frac{k}{k_j}\right) \quad \text{[Equation 1]}$$

Equation 2 presents the exponential model by Underwood (1961).

$$v = v_f e^{\left(-\frac{k}{k_c}\right)} \quad \text{[Equation 2]}$$

Equation 3 presents the North-Western model by Drake et al. (1965).

$$v = v_f e^{\left(-\frac{1}{2}\left(\frac{k}{k_c}\right)^2\right)} \quad \text{[Equation 3]}$$

Equation 4 presents the bi-linear (triangular) model by Daganzo (1994).

$$v = \begin{cases} v_f, & 0 \le k \le k_c \\ \frac{q_c}{k}\left(\frac{k_j - k}{k_j - k_c}\right), & k_c \le k \le k_j \end{cases} \quad \text{[Equation 4]}$$

Equation 5 presents the model by Van Aerde and Rakha (Van Aerde & Rakha, 1995; N. Wu & Rakha, 2009).

$$k = \frac{1}{a + \frac{b}{v_f - v} + c\,v} \; with \begin{Bmatrix} a = \frac{v_f(2v_c - v_f)}{k_j v_c^2} \\ b = \frac{v_f(v_c - v_f)^2}{k_j v_c^2} \\ c = \frac{1}{v_c k_c} - \frac{v_f}{k_j v_c^2} \end{Bmatrix} \quad \text{[Equation 5]}$$

Equation 6 presents the model by del Castillo and Benítez (1995).

$$v = v_f\left(1 - e^{\left(\frac{c}{vf}\left(1-\frac{k_j}{k}\right)\right)}\right) \qquad \text{[Equation 6]}$$

Equation 7 presents the model available in the Highway Capacity Manual (HCM) (Transportation Research Board & National Research Council, 2016).

$$v = \begin{cases} v_f, & 0 \le q \le q_b \\ v_f - (v_f - v_c)\left(\frac{q-q_b}{q_c-q_b}\right)^a, & q_b \le q \le q_c \\ \frac{q_c}{k_j}\frac{q}{q_c-q}, & k_c \le k \le k_j \end{cases} \qquad \text{[Equation 7]}$$

Equation 8 presents the s-shaped three-parameter model by Cheng et al. (2021).

$$v = \frac{v_f}{\left(1+\left(\frac{k}{k_c}\right)^m\right)^{\frac{2}{m}}}, \text{ with } m = \frac{2}{\log_2\left(\frac{v_f}{v_c}\right)} \qquad \text{[Equation 8]}$$

In all those models, the density k, the speed v and the flow $q = kv$ are the variables and all other quantities are constant parameters (which can differ for each road type and vehicle type, driver type, etc.).

The models by Greenshield, Underwood, Drake et al., Daganzo, Van Aerde and Rakha and Cheng et al. (Equation 1 to Equation 5 and Equation 8) require two, three or four of the following parameters to be known:

- v_f speed at entirely sparse traffic, free-flow speed (km/h)
- v_c speed at peak capacity, critical speed (km/h)
- q_c flow at peak capacity, critical flow, capacity (veh/h/lane)
- k_c density at peak capacity, critical density (veh/km/lane)
- k_j density at entirely jammed traffic, jam density (veh/km/lane)

4.2. Model calibration based on the Highway Capacity Manual

The Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine in the United States has published their first Highway Capacity Manual (HCM) in 1950. In January 2022, the seventh edition has been released. The manual does provide a speed-flow relationship (see Equation 7) for freeways and highways. It does also provide tables and formulas to obtain values for the parameters in this relationship. However, the same parameters can be applied to the other models. A previous study (Rohaert et al., 2022a) showed that the models by Daganzo (1994), by Van Aerde and Rahka (1995) and by Cheng et al. (2021) seem to fit well to empirical data related to routine traffic and to wildfire evacuations. These three models also show trends that are very similar to the model proposed for in the Highway Capacity Manual (see Figure 1).

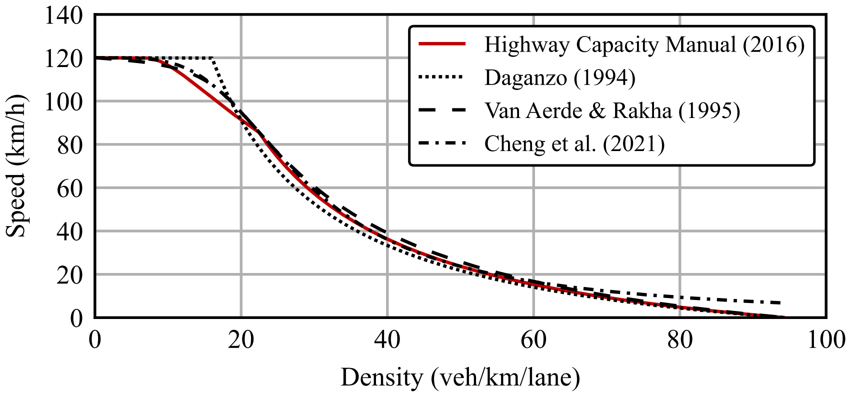

Figure 1. An example of the Daganzo model, the Van Aerde and Rahka model and the HCM model for a highway with a speed limit of 120 km/h. The same parameters have been used for all models. Note the models' similarity.

What follows is a summary on how to obtain the HCM parameter values.

Free-flow speed

When deriving the free-flow speed for a certain freeway or a multi-lane divided highway section, the speed limit is taken as base and adjustments are made to consider the influence of the number of lanes, the lane width, the lateral clearance, the median type, and the total ramp density.

Since these adjustments are small, it can be decided to assume that the free-flow speed equals the speed limit. As an example of this neglectable influence of the adjustments, on freeway US 101 in Santa Rosa, California, the free-flow speed was calculated according to (*Highway Capacity Manual*, 2016, eq. 12.3), considering the lane widths, lateral clearances, median type and access point density. Combined, those factors cause the free-flow speed of 104.5 km/h (64.9 mi/h) to be 0.12 km/h (0.08 mi/h) lower than the actual speed limit 104.6 km/h (65 mi/h).

Critical flow

In the HCM (2016), the critical flow (i.e. flow at capacity) is expressed in pce/h/lane, in which pce stands for passenger car equivalents. Generally, little is known about the traffic mix (share of passenger cars, busses, motorcycles, camper vans, lorries…). Therefore, the translation of 'passenger car equivalents' to 'vehicles' is simplified to a simple conversion (Dowling et al., 2016): one passenger car equivalent is assumed to equal 0.8 vehicles. According to the HCM (2016), the critical flow only depends on two factors: the type of road (freeway or highway) and free-flow speed. For highways, the critical flow can be calculated as shown in Equation 9 (*Highway Capacity Manual*, 2016, eq. 12.7).

$$q_c = \begin{cases} 800 + 9.94\, v_f, & v_f < 104.6 \\ 1840, & v_f \geq 104.6 \end{cases} \qquad \text{[Equation 9]}$$

The formula should not be used for free-flows lower than 72.4 km/h or higher than 112.7 km/h. For freeways, the critical flow can be calculated as shown in Equation 10 (*Highway Capacity Manual*, 2016, eq. 12.6).

$$q_c = \begin{cases} 1360 + 4.97\, v_f, & v_f < 112.7 \\ 1920, & v_f \geq 112.7 \end{cases} \qquad \text{[Equation 10]}$$

The formula should not be used for free-flows lower than 88.5 km/h or higher than 120.7 km/h. Both formulas are presented in Figure 2.

Critical density and critical speed
According to the HCM (2016), the critical density is a constant value, equal to 45 pce/mi/lane. Applying the same assumption as before, this converts to 22.4 veh/km/lane. Subsequently, the critical speed can be found by dividing the critical flow by the critical density. This leads to Equations 11 and 12 (and Figure 2).

For highways:

$$v_c = \begin{cases} 35.8 + 0.44\, v_f, & v_f < 104.6 \\ 82.3, & v_f \geq 104.6 \end{cases} \qquad \text{[Equation 11]}$$

For freeways:

$$v_c = \begin{cases} 60.8 + 0.22\, v_f, & v_f < 112.7 \\ 85.9, & v_f \geq 112.7 \end{cases} \qquad \text{[Equation 12]}$$

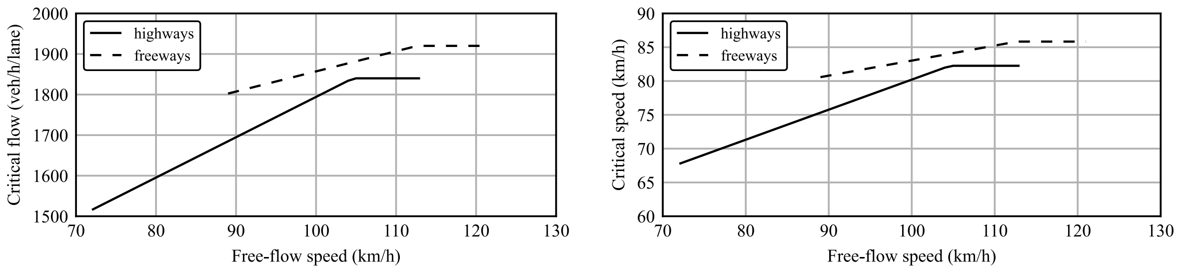

Figure 2. The critical flow (left) and the critical speed (right) according to the HCM (2016), as a function of the road type and the free-flow speed.

Jam density
According to the HCM (2016), the jam density is a constant value, equal to 190 pce/mi/lane. Applying the same assumption as before, this converts to 94.5 veh/km/lane.

Some models, like the model by Greenshields et al., Underwood, Drake et al. and Van Aerde and Rakha, only require (some) of these physically meaningful parameters. Table 1 provides the values of these parameters, for freeways and highways, according to the HCM (2016).

Table 1. Values for the HCM model parameters.

	v_f (km/h)	v_c (km/h)	q_c (veh/h/lane)	k_c (veh/km/lane)	k_j (veh/km/lane)
Freeway	120	85.8	1920	22.4	94.4
	110	85.2	1907	22.4	94.4
	100	83.0	1857	22.4	94.4
	90	80.8	1807	22.4	94.4
Highway	110	82.3	1840	22.4	94.4
	100	80.2	1794	22.4	94.4
	90	75.8	1695	22.4	94.4
	80	71.3	1595	22.4	94.4
	70	66.9	1496	22.4	94.4

Figures 3-5 present the models by Daganzo, by Van Aerde and Rakha, and by Cheng et al., employing the parameters from Table 1.

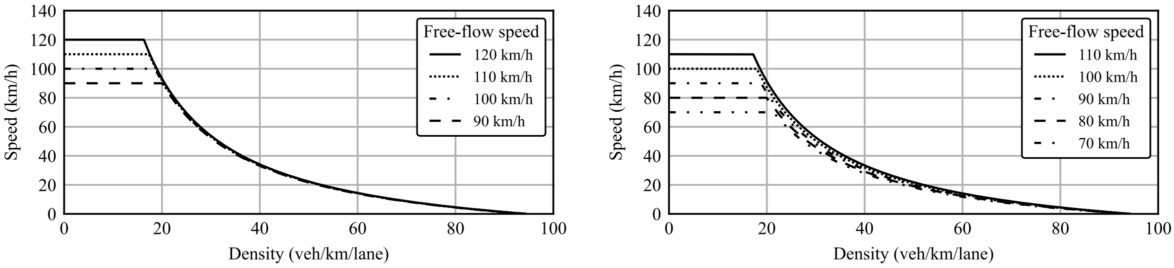

Figure 3. The Daganzo model for freeways (left) and highways (right) with different speed limits.

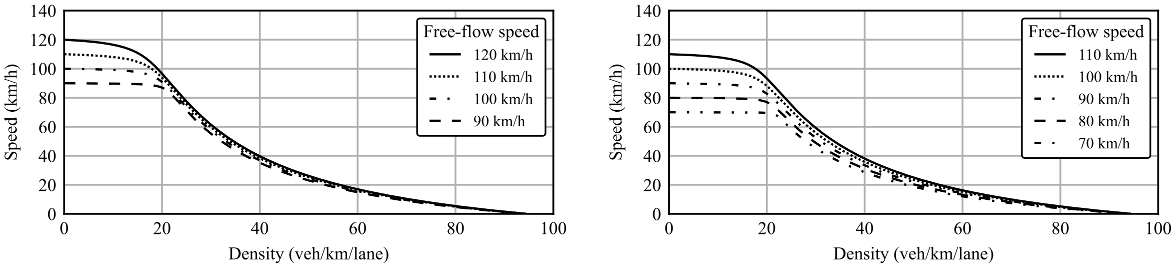

Figure 4. The Van Aerde and Rakha model for freeways (left) and highways (right) with different speed limits.

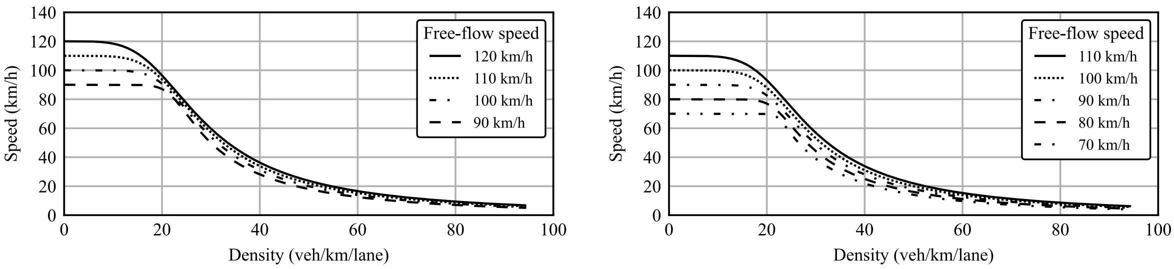

Figure 5. The model by Cheng et al. for freeways (left) and highways (right) with different speed limits.

The analysis of those macroscopic relationships show that key variables needed in a traffic evacuation database include velocity, density and flow.

4.3. Example of calibration in a microscopic model (SUMO)

In microscopic models, all vehicles are considered individually. Therefore, microscopic models are able to deal with heterogeneous traffic (different sub-models, different vehicles, different driving styles...). They can describe longitudinal (e.g. speed or acceleration) and lateral dynamics (e.g. lane-changing). To do so, microscopic models contain several sub-models. More information on their characteristics in the specific context of wildfire evacuation can be found in (Intini et al., 2019). As traditional traffic detection systems only provide measurements from discrete locations, they can only contribute to the car-following models, which describe the longitudinal dynamics.

Car-following models provide the speed and acceleration of a following vehicle, depending on the conditions in front of it. Many car-following models have been developed. One of these models is the model by Krauß (1998), implemented in Simulation of Urban MObility (SUMO), an open source traffic simulator developed by the Institute of Transportation Systems in Germany (Lopez et al., 2018). In steady-state conditions, this car-following model reduces itself to a speed-density relationship (see Equation 13).

$$v = \max\left(v_f, \frac{s-s_j}{\tau}\right) \qquad \text{[Equation 13]}$$

where

$s = 1/k$	is the distance headway,
$s_0 = 1/k_j$	is the distance headway in a jam (the sum of the car length and the minimum gap), and
τ	is the reaction time

This speed-density relationship is equivalent to the model by Daganzo. The critical density is the density for which the free-flow speed equals the speed in the congested phase (see Equation 14).

$$k_c = \frac{k_j}{1+v_f k_j \tau} \qquad \text{[Equation 14]}$$

In SUMO, passenger cars have a default length of 5m and a default minimum gap of 2.5m, which leads to a jam density of 133 pce/km/lane or 106.7 veh/km/lane. The reaction time has a default value of 1s. This leads to the parameters in Table 2 (applying the same conversion of 1 pce to 0.8 veh).

Table 2. Values derived from the default values in SUMO.

	$v_f = v_c$ (km/h)	q_c (veh/h/lane)	k_c (veh/km/lane)	k_j (veh/km/lane)
Any road type	120	2351	19.6	106.7
	110	2312	21.0	106.7
	100	2268	22.7	106.7
	90	2215	24.6	106.7
	80	2153	26.9	106.7
	70	2078	29.7	106.7
	60	1986	33.1	106.7
	50	1870	37.4	106.7
	40	1719	43.0	106.7
	30	1516	50.5	106.7

Figure 6 allows to compare the models obtained with parameters from HCM and from SUMO. The two sources lead to comparable results. The models that employ the default values of SUMO are essentially one curve (defined by the jam density and reaction time), capped at different free-flow speed. The parameters from HCM approximate this trend. Note that in SUMO, these parameters are not only used for freeways and highways, but also for arterials and collectors.

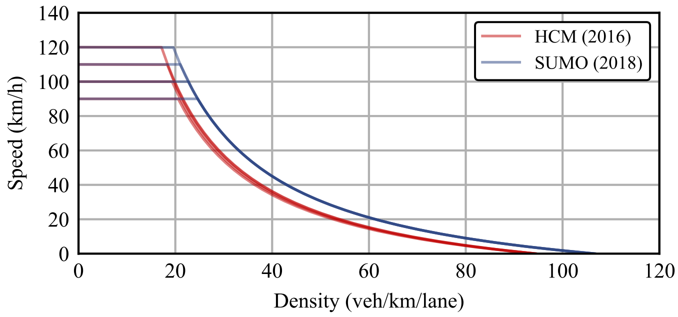

Figure 6. The Daganzo model for different free-flow speeds with parameters from HCM and SUMO.

4.4. Road types in OpenStreetMap and the Highway Capacity Manual

Since many traffic models (including WUI-NITY) make use of OpenStreetMap (OSM), a review of the road classification adopted there is a needed step to understand where data are applicable. Similarly, a commonly used document for road classification is the Highway Capacity Manual (HCM) (Transportation Research Board & National Research Council, 2016), thus it was needed useful to perform an equivalence of road categories in OSM and HCM. In OpenStreetMap (OSM), the road type is saved under the key *highway*. Table 3 lists different key values and describes them. Table 3 is a simplification of the table in the OSM documentation (OpenStreetMap Wiki, 2022a).

Table 3. Different road types present in OSM. Adjusted from (OpenStreetMap Wiki, 2022a).

Map style	Key value	Description
	motorway	the major highway with restricted access
	trunk	the most important roads that are not motorways
	primary	the next most important roads
	secondary	the next most important roads
	tertiary	the next most important roads
	unclassified	the least important roads other than residential roads
	residential	the roads that provide access to settlements
	road	the unclassified roads
	track	the roads for agricultural or forestry use, often unpaved

Apart from the road type, the road elements in OSM can be labelled with a speed limit as well, under the key *maxspeed* (OpenStreetMap Wiki, 2022b). While motorways, trunks and primary roads are typically labelled with a speed limit, other road types usually are not.

The Highway Capacity Manual (HCM) employs four categories for roads: freeways, highways, arterials, and collectors. Table 4 shows an example of equivalence of these categories to the road types of OSM.

Table 4. Proposed translation between road categories in OSM and HCM.

OSM	HCM
motorway	freeway
trunk	highway
primary	
secondary	arterial
tertiary	
unclassified	
residential	collector
road	
track	

4.5. Macroscopic model calibration for wildfire evacuation scenarios

In this section, it is explained how well-known macroscopic models can be fitted on traffic data from real wildfire evacuations. First, a database is chosen. Then, a data selection process is proposed, followed by a fitting technique.

4.5.1. Caltrans PeMS Database

The California Department of Transportation (Caltrans) commenced the Freeway Performance Measurement System (PeMS) in 1999, in cooperation with the University of California, Berkeley (California Department of Transportation, 2020, Chapter 1). Today, it collects real time traffic data from 46 516 detectors, stores them, and makes them available online[5] The data can be used to analyse the traffic dynamics and service quality. Moreover, the database contains incident records of the California Highway Patrol and lane closure records from Caltrans Headquarters (California Department of Transportation, 2020, Chapter 1).

Detectors

The 46 516 detectors are spread over 19 085 vehicle detection stations (VDSs). Of all those stations, 64% is equipped with inductive loops, 5% is equipped with radars and 3% with magnetometers. For 25% of all stations, the labels are missing.

The most common detector in PeMS is the loop detector. Loop detectors are essentially wires that are installed in a sealed loop-shaped saw cut, just beneath the road surface (Woods et al., 1994). The wire acts like a coil. When a vehicle moves over the coil, it will generate a vortex current in the loop and thereby decrease the loops inductance by a few percentages (Woods et al., 1994). Consequently, one loop can detect the traffic flow and the detector occupancy. Some VDSs are equipped with dual loops, which consist of two loops, typically positioned three to four meters apart from each other (Klein & Kelly, 1996). These dual loops can also obtain the vehicle speed as the ratio of the loop distance and the detection delay ($v = \Delta x / \Delta t$). The magnetometers operate in a similar way, as they also detect the disturbance of the ambient magnetic field. Magnetometers can determine the vehicle speed when at least two magnetometers are installed in series (analogue to the dual loops).

Accuracy

[5] https://pems.dot.ca.gov/

No studies have been done to determine the accuracy of the inductive loop of Caltrans. However, inductive loops are known for their high accuracy. Studies on similar loops in Minnesota show that the count (volume and flow) accuracy lies between 97.0 and 99.9 % when comparing it with a manual count from video footage and that the speed accuracy lies between 96.7 and 98.8% when comparing to the verified speedometer of a probe vehicle (Minnesota Department of Transportation, 2002). Research performed in Texas (Woods et al., 1994) reveals a mean error in vehicle speed of approximately 2.4 km/h (≈ 1.5 mi/h) for all speeds, in comparison to an infrared sensor speed trap. Note that the accuracy of the double loop detectors depends on the specifications of the detector (e.g., winding and shape of loops, distance between loops and calibration, type of cables, sealant), installation procedure, vehicle types, vehicles speeds, weather conditions, etc (Dailey, 1999; Minnesota Department of Transportation, 2002; Woods et al., 1994).

4.5.2. Data selection

To augment the reliability of the data extracted from PeMS, a data selection process is proposed. This process considers the five aspects below.

Detector position
Since the traffic dynamics on the mainline and on the ramps (junctions) are expected to differ, only the detector stations on the mainline of the highway are considered for this demonstration.

Speed measurement
Not all detector stations measure the speed. For those that do not, PeMS employs an algorithm to estimate the speed from nearby stations: the Daily Length Profile Algorithm by Erik van Zwet (Chen, 2002). To avoid noise and bias, only detector stations that measure the speed, are considered for this demonstration.

Detector health
The measurements of a detector station might be erroneous. The PeMS database does automatically identifies unreliable data and calculates the health (the percentage of reliable data) data that is produced by the detector station. To avoid unreliable results, only detector stations that have a health of 97% or more during the measurement campaigns, are considered for this demonstration.

Visual inspection
The detector stations that satisfy the three conditions above, are subjected to a visual inspection. First, they are located on satellite images to ensure that all lanes belong to the mainline, and not to a junction or weaving zone. The location indeed should belong to a section which is long enough and far from junctions in both directions. Second, graphs are created that display the evolution of speed, flow, and density over time for each lane, as well as graphs that relate the speed, flow, and density. Only stations for which the graph show physically credible results are considered for this demonstration.

Spacing
Next, a selection is made to consider as much stations as possible, considering a spacing between selected stations of at least 2 km. We made this decision to compromise the size of the data set and the correlation of the data.

4.5.3. Model fitting

The macroscopic models can be fitted to traffic data by minimizing the weighted least-squares of the residuals (error on the speed-prediction) by means of the Levenberg-Marquardt algorithm, which interpolates between the Gauss-Newton algorithm and the method of gradient descent (Levenberg, 1944; Marquardt, 1963).

The least-squares are weighted to improve the fit over the entire range of densities. This because light traffic is usually more common than heavy traffic over the span of a full day. Consequently, the distribution of traffic data is often significantly imbalanced, and an ordinary model fit would fit better in the low-density zones then in the high-density zone. To counteract this bias, the weighted least-square method is applied, as proposed by Qu et al. (2015). Here, the data set is sorted so that $k_1 < k_2 < \cdots < k_i < \cdots < k_m$. The weights are defined as given in Equation 15.

$$\min S = \sum_i^m w_i \left(v_{i,observed} - v_{i,predicted}\right)^2 \qquad \text{[Equation 15]}$$

where

$$w_i = \begin{cases} k_2 - k_1, & i = 1 \\ (k_{i+1} - k_{i-1})/2, & i = 2, 3, \dots, m-1 \\ k_m - k_{m-1}, & i = m \end{cases}$$

4.5.4. Average vehicle length

The detectors do not just measure the vehicle speed v and the flow q. They also measure the occupancy o, which is the fraction of the sampling period for which a vehicle is present at the detector's location. For a given velocity, longer vehicles will occupy the detector longer and vice versa. Assuming that the length and speed of a vehicle are independent, the vehicle length l can be calculated as follows (Chen, 2003a, Chapter 6; Dailey, 1999):

$$l = vo/q \qquad \text{[Equation 16]}$$

where, l is the arithmetic average length (m/veh) of all vehicles passing by the detector, v is the average speed (m/s), o is the detector's occupancy (-), and q is the flow (veh/s) passing by the detector (all during the five-minute interval). Equation 10 allows the investigation of the difference in vehicle types during evacuation scenarios in comparison with routine traffic.

4.6. Traffic Data Analyser

Previous work (Rohaert et al., 2022a) highlighted that more data should be gathered from different wildfires to be able to describe general trends. In order to reduce duplication of efforts, a tool with a graphical interface (Figure 7) was developed to extract data from different vehicle detection stations at different periods (scenarios) and automate the analysis. The tool, called Traffic Data Analyser (TDA), is published in open access on Github and Zenodo (Rohaert, 2022). What follows is a short description of the different uses of the tool.

Automated data extraction

The tool is able to log into the PeMS platform and extract all required data automatically. Consequently, it does process the data (executes the necessary conversions, calculates the density and the average vehicle lengths). For instance, for the case study of the Glass Fire included in this report, it was necessary to download 200 files (2 files/detector/timespan * 25 detectors * 4 timespans). Manually requesting these files from the PeMS database would be cumbersome.

Visual inspection

The tool can produce graphs for each detector individually. It can produce scatter plots of the speed, flow and densities that have been observed for each lane. It can also provide the speed, flow and density time series. These graphs are valuable to perform a visual inspection of the data.

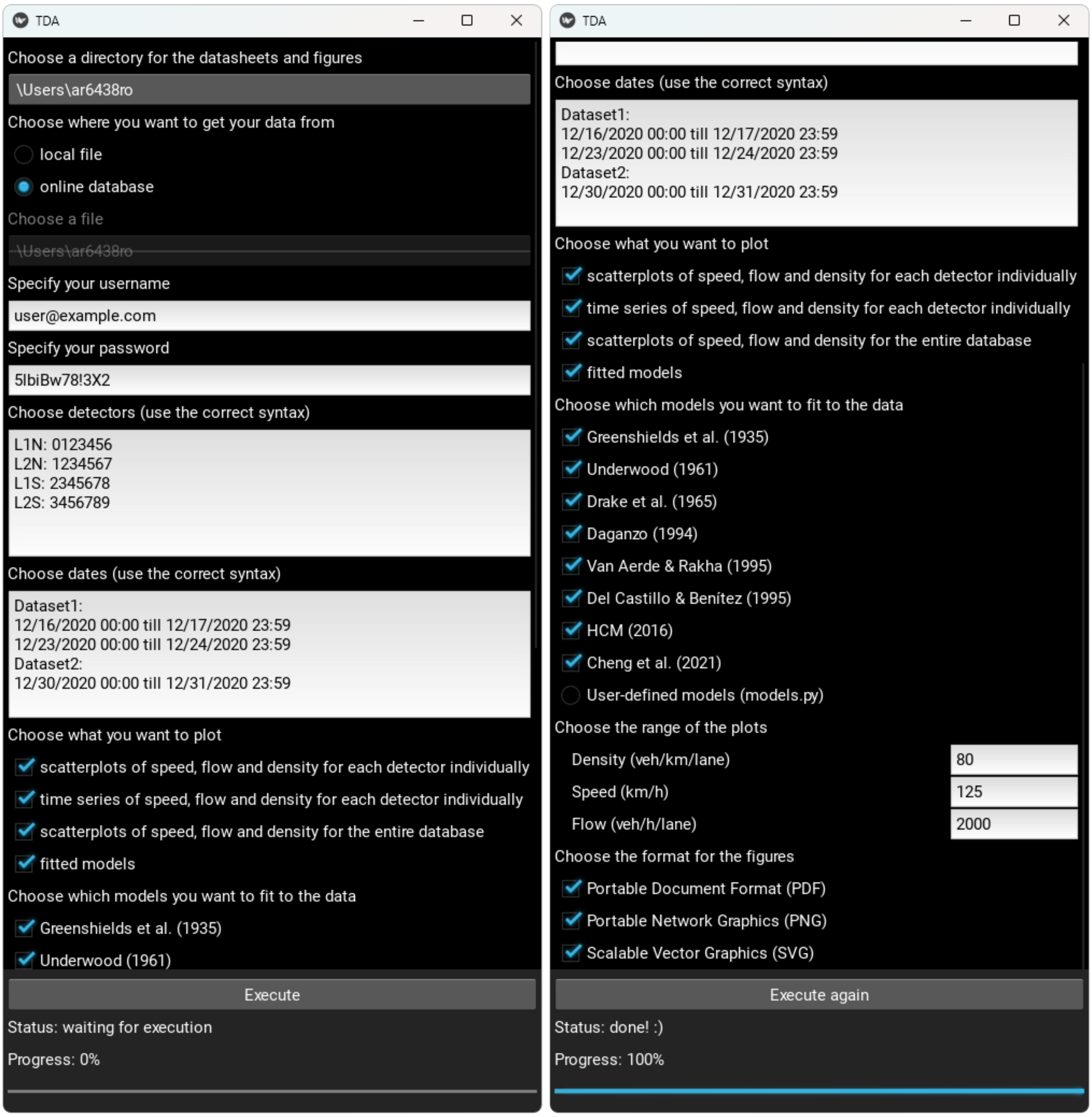

Figure 7. The graphical user interface of the Traffic Data Analyser.

As an illustration, the scatter plot of station 406302 is shown in Figure 8 during the Glass Fire evacuation. The observed values are unreasonably when compared to the values of the other detectors on the same highway. The investigation of satellite pictures of the location (Figure 9), revealed that the lanes do not longer perfectly align with the induction after construction works. Most likely, the induction loops of the slow lane register the vehicles in the fast lane as well, leading to erroneous, high densities. In a similar way, it is possible to recognise detector that are positioned on ramps on weaving zones, or detectors that are “stuck” on certain values.

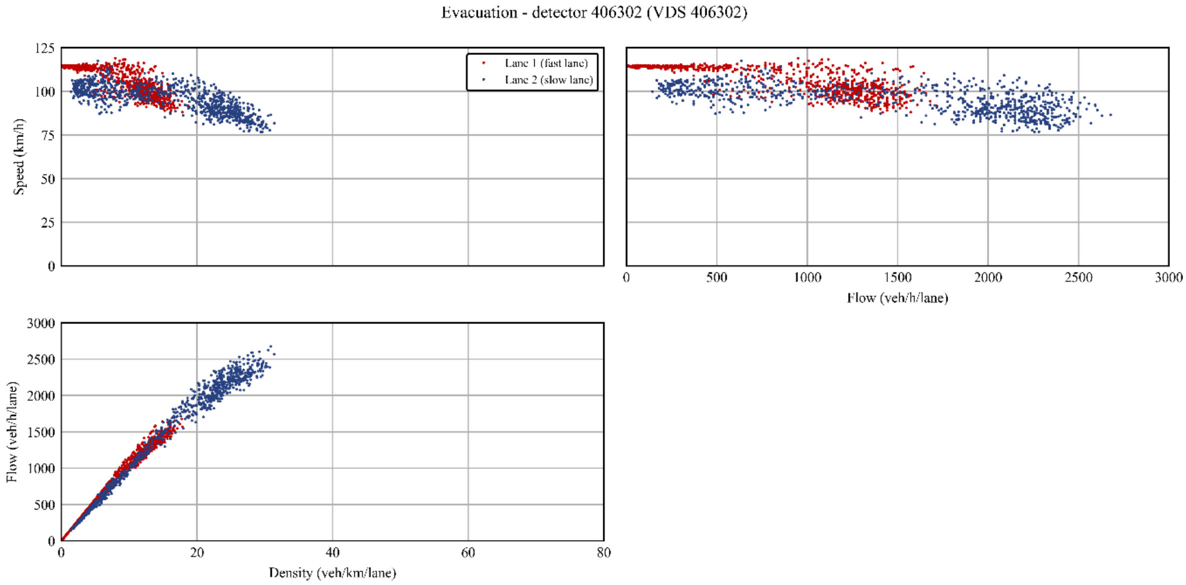

Figure 8. The speed, flow and density scatter plots for the faulty station 406302. The observed values are unreasonably high, likely due to a bad alignment of the inductive loops and the lanes.

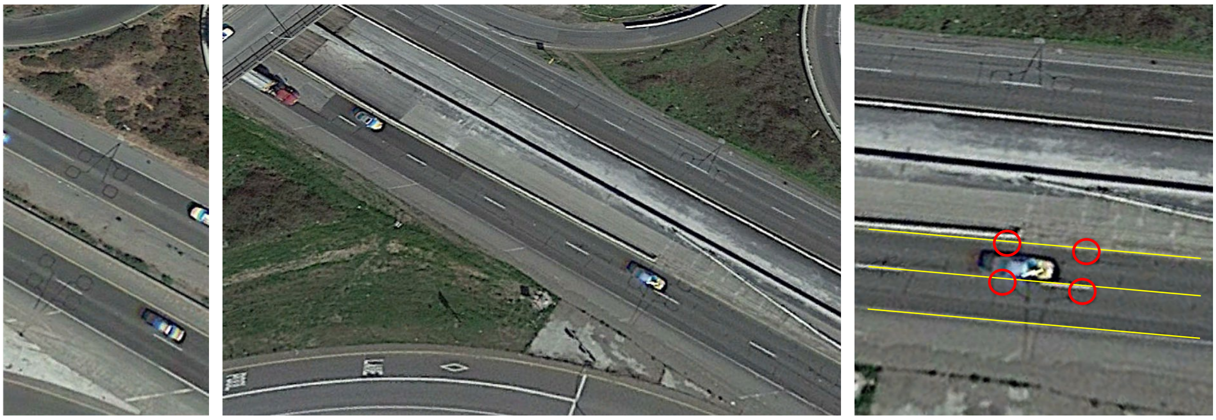

Figure 9. Satellite pictures of station 406302. Left: a satellite picture from September 2018, when the loops align with the lanes. Centre and right: a satellite picture from February 2021, when the loops do no longer align. Satellite pictures obtained from Google Earth.

Scatter-plots of the speed, flow and density

The tool can produce scatter graphs of all scenarios. These allow to visually compare the difference in traffic dynamics.

Model fitting

The tool is able to produce model fits, as described in the sections above. Doing so, trends can be compared quantitative. Besides the graph, a datasheet is created that contains the values of the fitted parameters, as well as the confidence interval of these values. An example is provided in Figure 10.

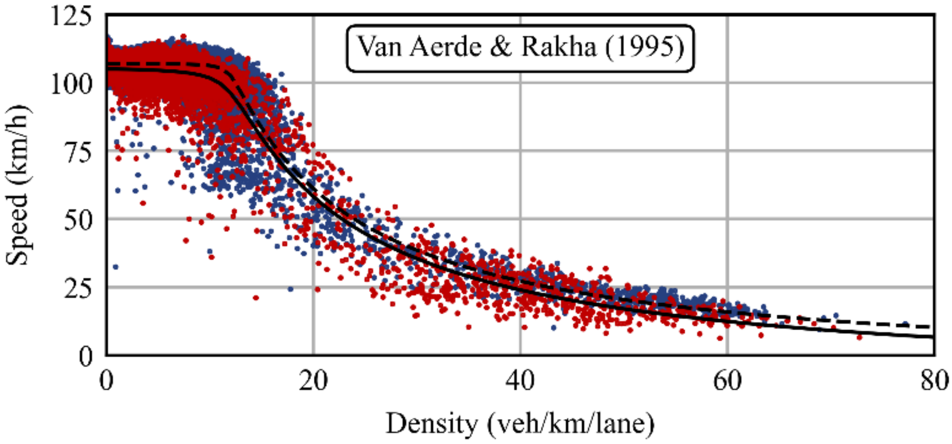

Figure 10. The scatter graph of speed, flow and density for routine traffic (blue) and evacuation traffic (red) before and during the 2019 Kincade Wildfire. The full line presents the fit of the model by Van Aerde & Rakha to the evacuation data, while the dashed line is fitted to the routine data. Figure from (Rohaert et al., 2022a).

5. Open access WUI fire evacuation case studies

As mentioned before, there is a clear need for more data regarding traffic movement during emergency response is apparent (Wong et al., 2020). Therefore, two case studies are presented below: the 2020 Glass Fire in Sonoma and Napa, California, and the 2020 Silverado Fire in Orange County, California. The Case studies also demonstrate the use of TDA. In case official data or information were lacking, information from media sources and other types of reports were used to supplement our work.

5.1. The 2020 Glass Fire

The Glass Fire was chosen as it led to a large-scale evacuation. Moreover, the US Highway 101, which is located just next to the evacuation zone, is equipped with dual loop detectors, which allow measured flow, speed, and occupancy at the time of the evacuation. In this section, a short overview of the event is given, and the data selection process is revealed. At last, the results are shown and briefly discussed.

5.1.1. Short overview of the 2020 Glass fire events

The 2020 Glass Fire started on the 27th of September, 2020 right before four o'clock in the morning and continued burning for 24 days until it was fully contained (on the 20th of October, 2020) (*CAL FIRE 2020 Fire Siege*, 2020). The ignition point was located in Napa County, California, United States, but the fire expanded rapidly to Sonoma County, due to the extreme high temperatures, strong winds and unprecedented drought. By the second day, about 14 700 hectares (36 400 acres) of land were affected, which is more than half of the eventually affected area (27 300 hectares or 67 500 acres) (*CAL FIRE 2020 Fire Siege*, 2020). The ignition point and final perimeter of the fire are displayed in Figure 11.

The second day, the fire reached the cities of Santa Rosa, Calistoga, and Saint Helena. In total, 1 555 structures were destroyed (*CAL FIRE 2020 Fire Siege*, 2020) (of which 42% was estimated to be residential) and 282 structures were damaged (of which 57% was estimated to be residential)[6], making this fire the tenth most destructive wildfire in California so far (California Department of Forestry and Fire Protection, 2022).
Both Sonoma County and Napa County are divided into zones to manage evacuations during emergencies. In Sonoma, all evacuation orders were issued on the 27th and the 28th of September while in Napa, the last order was issued the 4th of October. All orders were lifted between the 2nd and the 19th of October[7]. The evacuation zones for which an order or warning was released, are displayed in Figure 11.

5.1.2. 2020 Glass Fire data selection

Only one route in the vicinity of the evacuation zones has been equipped with vehicle detection stations (VDSs): the federal highway US 101. This highway, accessible for most evacuees, runs straight through the Sonoma Valley and it is the only route with multiple lanes in each direction and grade-separated junctions. The highway has a speed limit of 65 mi/h (≈ 105 km/h).
All VDSs along US 101 in Sonoma County have been considered for data extraction. The selection process has been summarized in five steps (see Section 5.5). It has been applied to the 301 available vehicle detection stations, located along the US 101 in Sonoma County. The outcome is summarized in the flowchart below (see Figure 12). Eventually, fifteen stations were discarded after the visual inspection. For seven of these stations, detectors were present on an on-ramp, an off-ramp, or a weaving zone, despite them being labelled as "mainline" in the

[6] https://twitter.com/CALFIRELNU/status/1315288065540149248/photo/1
[7] https://abc7news.com/glass-fire-napa-update-news-calistoga-wildfire/7194134

PeMS database. The other seven discarded stations had one or more detectors that produced unreliable data.

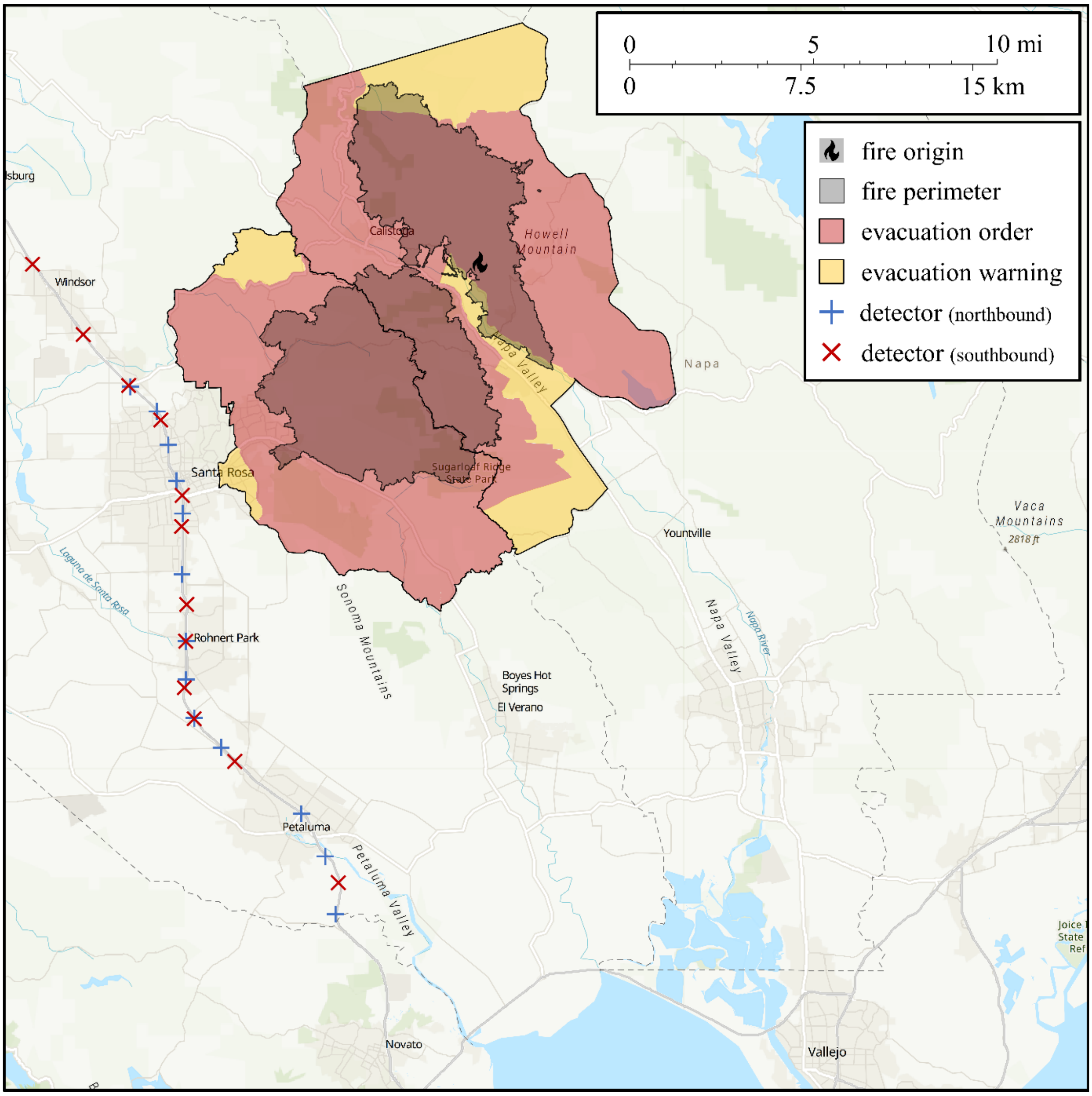

Figure 11. Map (ESRI) of the wildfire incident. The mandatory evacuation orders for both Sonoma and Napa are coloured red, while the evacuation warnings are coloured in yellow. The final perimeter of the fire is coloured black. The ignition point (CAL FIRE 2020 Fire Siege, 2020) is marked with the symbol of a flame.

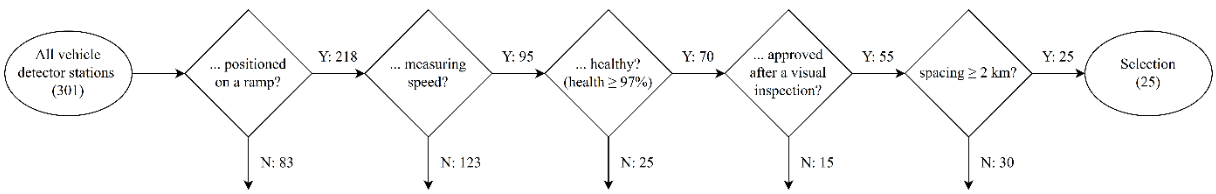

Figure 12. Flowchart of the selection process for the vehicle detection stations. The word "healthy" refers to the estimated the percentage of reliable data from the detector.

The final selection of VDSs is listed in Table 5.

Table 5. Identification number of the selected vehicle detector stations (readers are referred to the PeMS database for the location of the detectors).

Northbound	Southbound
424573	424611
415667	416620
406287	406577
406553	409712
406554	401766
406557	401601
406562	401599
401598	402126
401602	409722
402129	409733
409674	409728
409673	410545
409668	

The first evacuation orders were issued on Sunday the 27th of September. However, this day, only low traffic densities (k < 30 veh/km/lane) are observed. For this reason, the evacuation scenario is considered to occur from Monday the 28th till Wednesday the 30th of September (Week 40). Note that it is necessary to consider weekday and weekend days separately, as traffic dynamics typically differ between these two. The routine data is taken one week earlier (Week 39), two weeks earlier (Week 38) and four weeks earlier (Week 36), from Monday till Wednesday as well. The reason that Week 37 is not considered, is because of Labor Day, on Monday the 7th of September. This day, traffic flow is significantly different and traffic dynamics are also considered to differ (as "weekend"-dynamics are expected).

Table 6 summarizes during which dates data is extracted. The average flow in these periods is also shown.

Table 6. Time periods of data extraction (day/month) and the corresponding flow. The Traffic flow indicates the average count on all detectors divided by three as this is measured during three days to ensure data are not sensitive to a single day event.

Scenario	Start	End	Week	Traffic flow (veh/day)
Routine	Monday 08/31	Wednesday 09/02	36	22399
	Monday 09/14	Wednesday 09/16	38	22140
	Monday 09/21	Wednesday 09/23	39	22690
Evacuation	Monday 09/28	Wednesday 09/30	40	22295

The data has been extracted, processed, and released. Open access to the data is provided for all interested parties (Rohaert et al., 2023).

PeMS also provides incident reports. Appendix 1 contains a summary of all incidents reported during the measuring periods. Most of them are signalled traffic hazards. None of the incidents led to lane closures or influenced the traffic dynamics significantly.

5.1.3. 2020 Glass Fire data analysis

Figure 13 shows the traffic flow on the highway. The hourly flows are an average of the flow of all detector stations. Here, routine data is shown up to six weeks before the week of evacuation (Week 40). The earliest week is Week 34, on which the new school year was started. It can be easily noticed that the routine traffic flows are regular. The one exception is Monday the 7th of September 2020 (Week 37), as it is a national holiday (*Labor Day*).

The fire starts on Sunday the 27th of September. The traffic flow is clearly affected the night between Sunday and Monday (see the most right end side of Figure 13). The flow is higher than usual until Monday noon. Also on Wednesday and Thursday, slightly higher flows are observed. From Friday on, the flow seems to be restored.

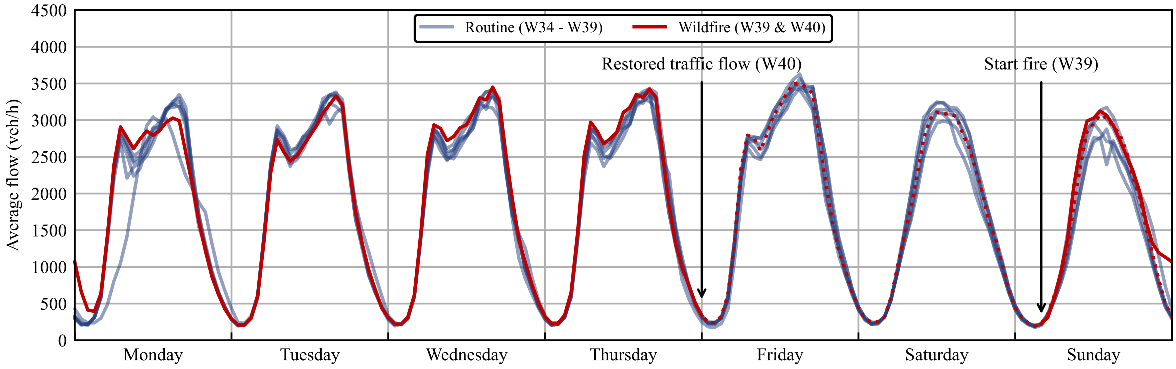

Figure 13. Average traffic flow before and during the wildfire.

The first evacuation orders are issued on Sunday. This day, the traffic flow is clearly affected, especially in the late evening with an increase of traffic compared to routine conditions. However, no congestion occurs in this period. This is clearly illustrated by Figure 14. The routine data in this graph is data from the Sundays one week, two weeks and four weeks before the evacuation.

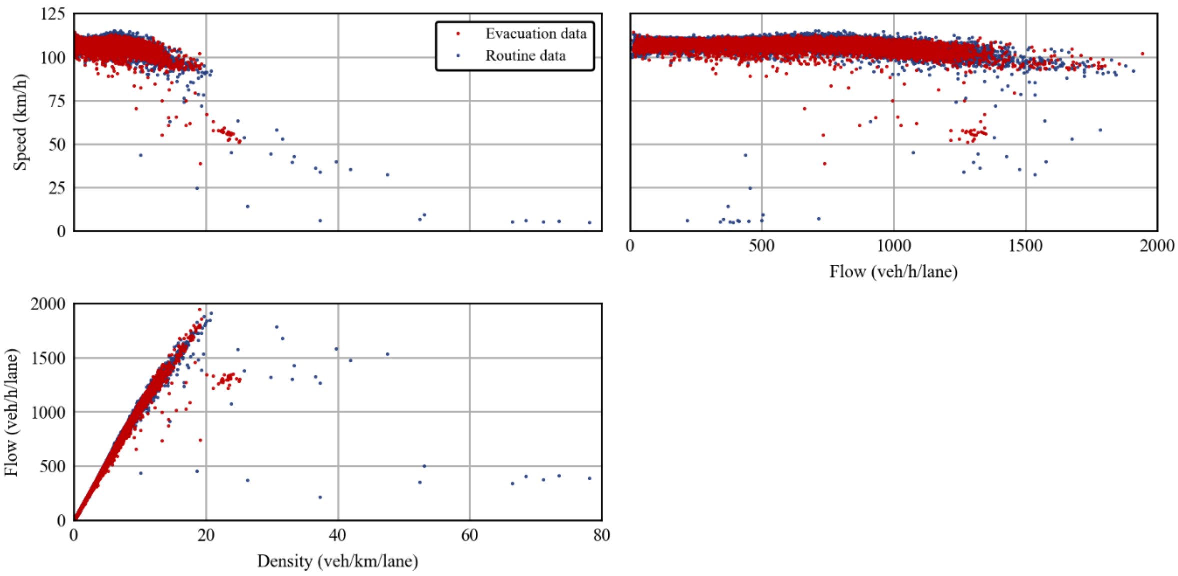

Figure 14. Speed-density, speed-flow, and flow-density scatterplot of the evacuation and routine data for Sunday, the 27th of September. Routine data is taken from the Sundays one week, two weeks and four weeks before the start of the wildfire. Note that no high traffic densities are reached during the first day of the evacuation.

Since no high densities are reached on Sunday, and different traffic dynamics typically occur during weekend days, data from Monday till Wednesday has been considered as the evacuation scenario (see also Table 6). Figure 15 shows the same scatterplot for this period. Clearly, congestion does occur these days. However, most of the datapoints have a low traffic density (98.6 % of all points has a density below 20 veh/km/lane). This confirms the need of weighting when fitting the data.

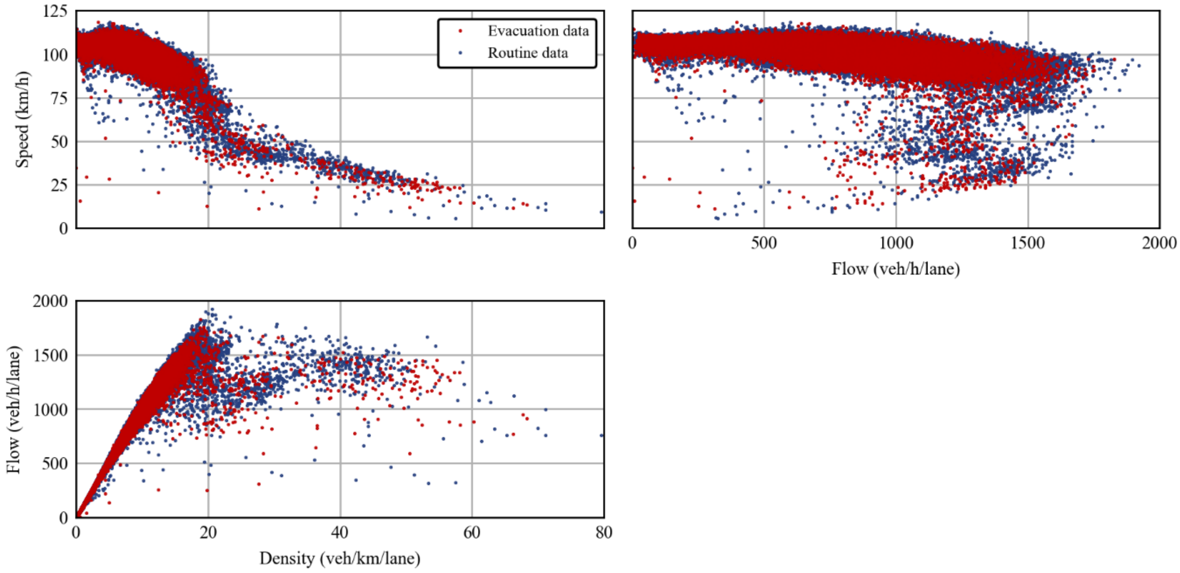

Figure 15. Speed-density, speed-flow, and flow-density scatterplot of the evacuation and routine data.

The trends of the evacuation and routine data are presented in Figure 16 as a weighted average, using triangular kernel smoothing. Triangular kernel smoothing is a method of smoothing noisy data by replacing each data point with a weighted average of its neighbours. The weights are based on a triangular function (called a kernel) that assigns higher weights to nearby points and lower weights to more distant points. Specifically, for each data point, the weight of all neighbours decreases linearly until 0 for all neighbours that differ from the data point with 5 veh/km/lane or more. Note that this nonparametric method provides a regression without assuming any underlying speed-density relation, nor a distribution for the variation. The same kernel smoothing has been applied to the 5 and 95 percentiles, which are calculated by linear interpolation from the empirical cumulative distribution function, as proposed by Parzen (1979). This way, the asymmetry and heteroscedasticity of the variance are disclosed without assuming its distribution.

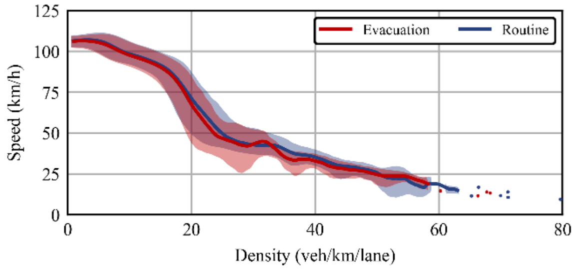

Figure 16. The weighted average of the speed presented as a line and the surface between the 5 and 95 percentiles. The smoothing is only drawn where the kernel covers more than five data points.

The model by Daganzo, the model by Van Aerde and Rakha, the HCM model and the model by Cheng et al. are fitted to the data. The values of the optimal model parameters are listed in Table 7. The table also provides the confidence margin of the parameters and the ratio φ which represents the value of the parameter during the evacuation scenario, relative to the value during the routine scenario. Figure 17 presents the curves graphically.

Table 7. Best fit values and confidence margin of the model parameters.

Model	**Parameters / WRMSE (unit)**	**Value (best fit ± 95% confidence margin)**				**φ (%)**
		Routine		**Evacuation**		
(Daganzo, 1994)	v_f (km/h)	102.1	± 0.12	101.7	± 0.21	99.6
	k_c (veh/km/lane)	14.1	± 0.03	13.6	± 0.05	96.3
	k_j (veh/km/lane)	192.2	± 2.14	230.8	± 7.58	120.1
	WRMSE (km/h)	6.19		6.98		
(Van Aerde & Rakha, 1995)	v_f (km/h)	105.8	± 0.17	105.0	± 0.29	99.2
	a (km lane/veh)	4.58E-03	± 6.9E-05	4.16E-03	± 1.5E-04	90.7
	b (km² lane/veh/h)	1.59E-01	± 7.7E-03	1.29E-01	± 1.3E-02	81.0
	c (h lane/veh)	5.83E-04	± 3.0E-06	6.25E-04	± 6.3E-06	107.3
	WRMSE (km/h)	5.96		6.77		
(HCM, 2016)	v_f (km/h)	106.4	± 0.19	106.2	± 0.35	99.8
	k_c (veh/km/lane)	16.0	± 0.07	15.4	± 0.13	96.6
	k_j (veh/km/lane)	182.1	± 1.88	208.9	± 6.16	114.7
	q_b (veh/h/lane)	544.1	± 42.99	477.0	± 81.18	87.7
	q_c (veh/h/lane)	1447.1	± 2.43	1391.8	± 4.42	96.2
	a (-)	1.09	± 0.12	1.14	± 0.22	104.7
	WRMSE (km/h)	5.88		6.64		
(Cheng et al., 2021)	v_f (km/h)	109.2	± 0.19	109.0	± 0.34	99.8
	k_c (veh/km/lane)	24.5	± 0.06	24.0	± 0.12	97.6
	m (-)	2.3	± 0.01	2.3	± 0.03	99.2
	WRMSE (km/h)	6.36		7.32		

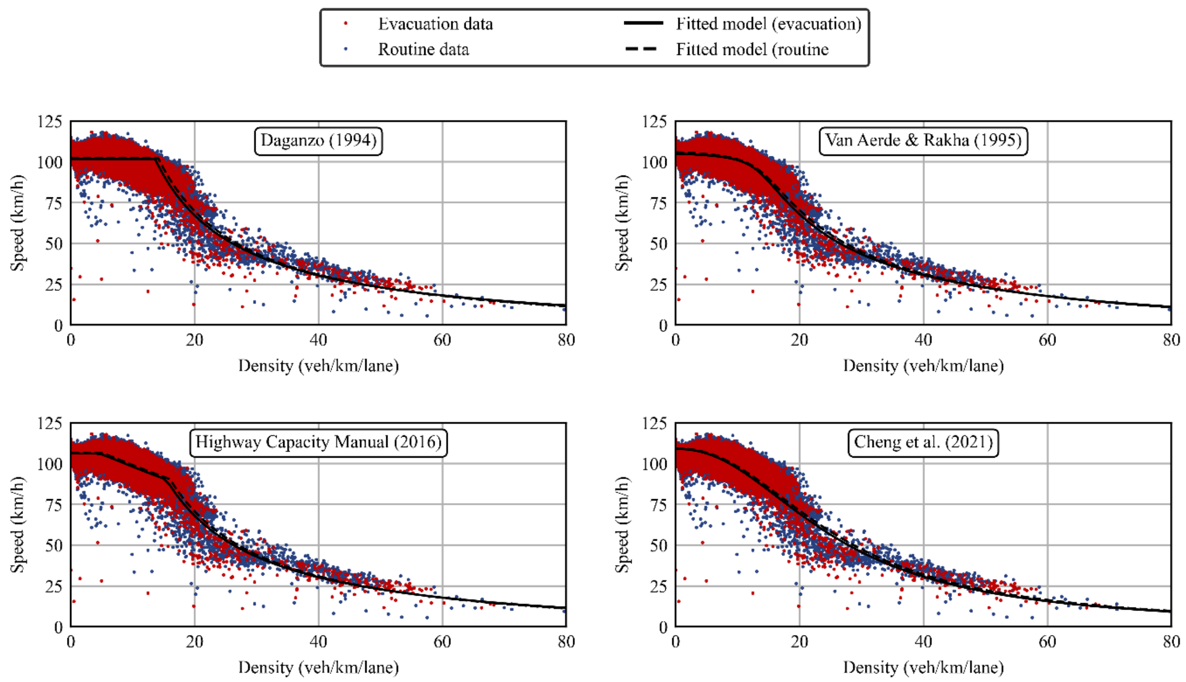

Figure 17. Density-speed curves of the fitted models for the evacuation data and the routine data.

Figure 18 visualises the sample distribution of average vehicle lengths for the evacuation and routine scenario. Both the histogram and the cumulative probability are constructed by weighting the average vehicle lengths with the flow of the interval and lane in question, to obtain car-based distributions and not lane-based distributions.

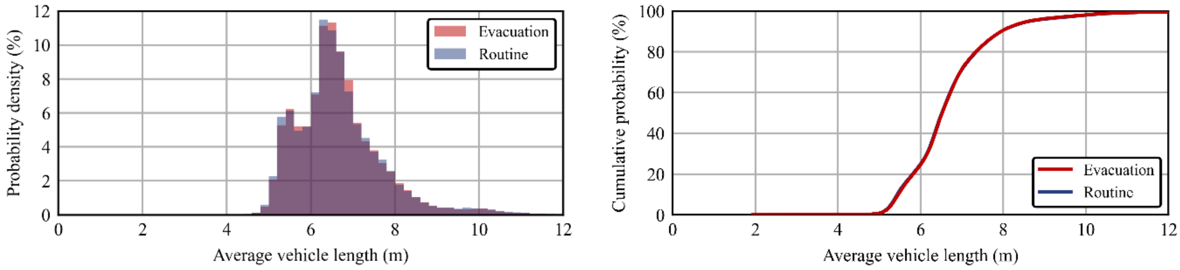

Figure 18. Probability density and cumulative probability of the average vehicle length.

One year earlier, the 2019 Kincade Fire caused an evacuation in Sonoma as well. Recent studies (Rohaert et al., 2022a) have shown that during this wildfire evacuation, traffic dynamics were different than the usual routine traffic. The speeds were reduced with about 3.5 km/h for densities between 0 and 64 veh/km/lane. The capacity was reduced with about 5%.

During the 2020 Glass Fire evacuation, such effects were not as noticeable on the US 101. It should be noted that the curves in Figure 17 are characterized by a low number of datapoints in the region of mid density around 30 veh/km/lane. The difference between the Kincade Fire and the Glass Fire is the position of the evacuation zones in relation to US 101. During the Kincade Fire, the US 101 run straight through the evacuation zones. During the Glass Fire, the US 101 is only in close vicinity. Consequently, it can be expected that the share of background traffic is higher during the latter.

There has been observations that evacuees have chosen to leave with boat trailers, caravans, campers, or vans during wildfire and hurricane evacuations (Maghelal et al., 2017; H.-C. Wu et al., 2012). As these vehicles occupy more space on the road, this might (partly) explain the reduced road capacity (when expressed in vehicles rather than passenger car equivalents). In 2019, the average vehicles lengths were considerably higher during wildfire evacuation. As clearly visualised in Figure 18, this was not the case in 2020. Figure 18 therefore substantiate the assumption that ‘background traffic’ was dominant on US 101 during the wildfire evacuation, diluting the effect of the wildfire evacuation on the traffic dynamics.

5.2. The 2020 Silverado Fire

This section introduces the 2020 Silverado fire as well as the major highways impacted during the event. Next, the data selection process is briefly described, and the section ends with a presentation of the findings.

5.2.1. Short overview of the 2020 Silverado fire events

The 2020 Silverado Fire affected southern Orange County, California, northeast of Irvine, in October and November 2020. The fire started on 26 October 2020, around 6:49 am, near Orange County Route S-18 (Santiago Canyon Road) and Silverado Canyon Road. Low humidity and strong Santa Ana winds of up to 80 mi/h (130 km/h) fuelled the fire. The Silverado fire destroyed five and damaged eleven structures and was contained on 7 November 2020. The fire burned approximately 50.5 km^2 of land. Figure 19 shows the Silverado fire's location and perimeter in the city of Irvine within Orange County, California.

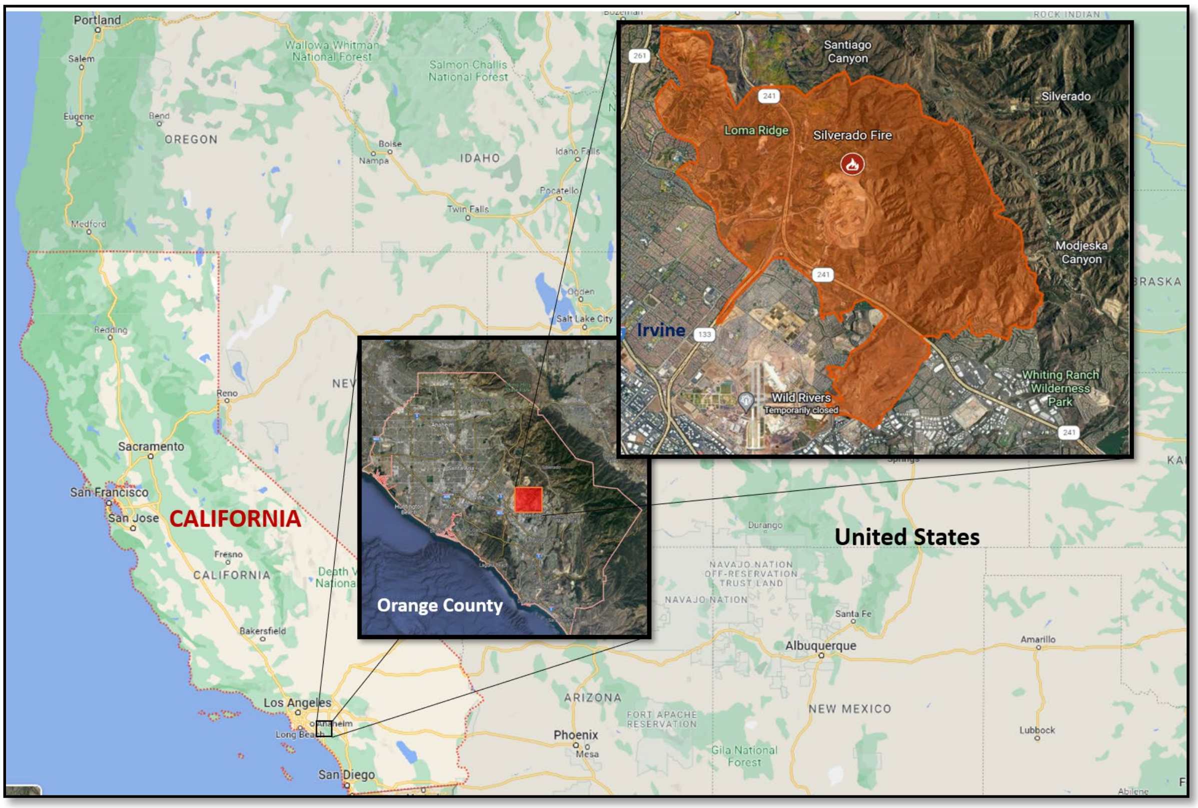

Figure 19. Location, and perimeter of the Silverado fire in Irvine, Orange County, California (based on Google maps).

Orange County Fire Authority and CalFire issued mandatory evacuation orders to manage the incident. No official timetable has been made available for the Silverado fire evacuation warnings and orders. However, according to the media reports[8], the conditions and time sequence of the evacuation warnings/orders were as follows:

1) The first round of mandatory evacuations was ordered in Orchard Hills, affecting approximately 60,000 residents east of Irvine on 26 October (Monday, 9:00 am). A thick layer of smoke was affecting those who lived north of Irvine Boulevard from Bake

[8] https://www.mercurynews.com/2020/10/27/silverado-fire-forces-90000-to-evacuate-2-firefighters-critically-burned/

Parkway to Jamboree Road, and the air quality was poor. Residents were ordered to leave their homes north of Irvine Boulevard.

2) On 26 October, just before 2 pm, Irvine city officials notified residents of another round of mandatory evacuations for Irvine Boulevard, Trabuco Road, Jeffrey Road, and Portola High School.
3) On Monday afternoon (after 2 pm), the mandatory evacuation orders spread to Lake Forest, requiring Baker Ranch and Foothill Ranch residents to evacuate.
4) Overall, a total of 90,800 people were ordered to evacuate by nightfall on Monday, 26 October.

Based on news articles[9] and the city of Irvine's official website[10], Figure 20 shows the evacuation zones that had been ordered to evacuate by 9:42 am on 26 October 2020 (labelled in the Figure 20 and referenced again in Table 8). The Orange County Fire Authority lifted all evacuation orders in Irvine at 4 pm on 28 October 2020. the times and the zones in which evacuation warnings or orders were issued in the city of Irvine and Lake Forest were obtained from media sources and the official city websites[11,12] and collected them in Table 8 and Table 9 (which is accompanied by Figure 21).

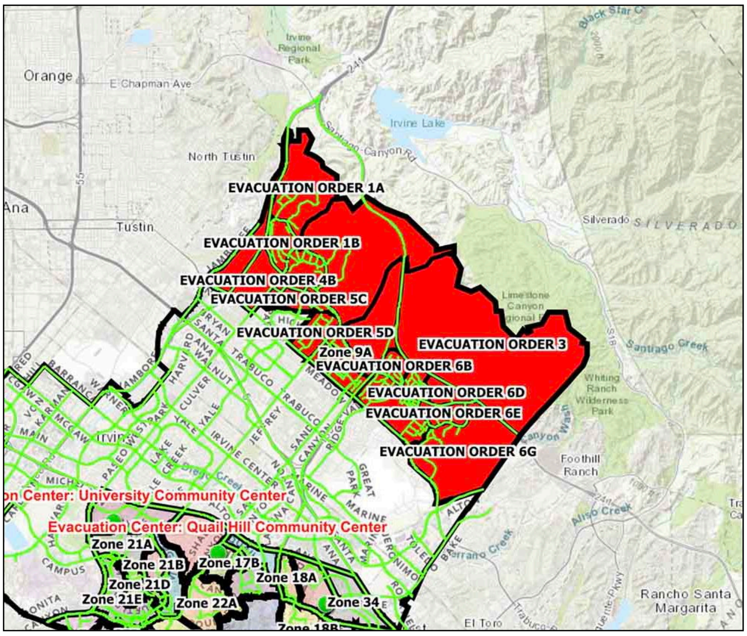

Figure 20. The evacuation-related state of the zones during Silverado fire at 9:42a.m. PDT Oct. 26, 2020 (based on city of Irvine's website).

[9] https://wildfiretoday.com/2020/10/26/ilverado-fire-in-orange-county-southern-california-threatens-structures/
[10] https://www.cityofirvine.org/news-media/news-article/silverado-fire-update-evacuation-orders-remain-place
[11] https://www.cityofirvine.org/office-emergency-management
[12] https://www.lakeforestca.gov/1042/Wildfires

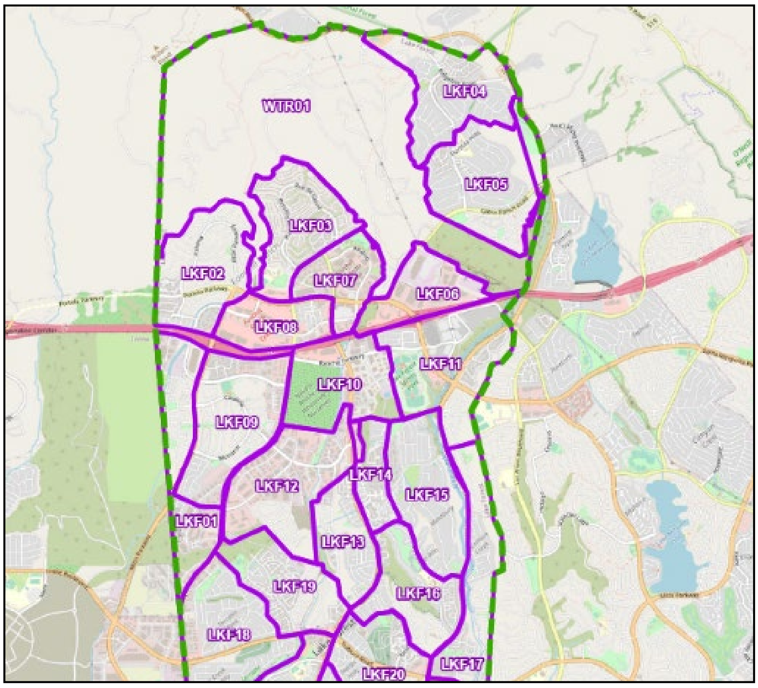

Figure 21. Evacuation zones in the city of Lake Forest (based on Google maps).

Table 8. Evacuation warning or order effective time and lifted time by date for the evacuation zones affected in the city of Irvine.

Order effective time	Order lifted time	Zone
26th October, 9:00 am (mandatory)		(Orchard Hills [1A-1D], Limestone Canyon Open Space, Lower Peter's Canyon [4A, 4B], Northwood Point [5C], Eastwood [5D], Portola Springs [6A-6F, 6H], Pavilion Park [6G], Marshburn Basin [6I], Stonegate [9A, 9B], Altair [51A]
26th October, before 2:00 pm (mandatory)		Woodbury [9D], Novel Park [51B], Beacon Park [51C, 51G], Cadence Park [51D, 51E], Rise [51F], Northwood [8C]
26th October, at evening (Warning)		Northwood [8F], Cypress Village [40A-40C], Great Park [51J]
	28th October, 04:00 pm	All evacuation orders have been lifted.

Table 9. Evacuation warning or order effective time and lifted time by date for the evacuation zones affected in the city of Lake Forest.

Order effective time	Order lifted time	Zone
26th October, 11:10 am (warning)		1
26th October, 11:30 am (warning)		1, 2, 3, and 9
26th October, 03:15 pm (mandatory)		1, 2, 3, and 9
26th October, 03:45 pm (warning)		4, 5, 6, 7, and 8
26th October, 04:30 pm (mandatory)		4, 5, and 6
	28th October, 03:00 pm	1, 2, 5, 6, 7, 8, and 9
	29th October, 11:00 am	All remaining evacuation orders have been lifted

The highways and freeways that serve as evacuation routes for the affected areas within Orange County (City of Irvine and City of Lake Forest) are Santiago Canyon Road, SR241, SR133, SR261, and Freeways I-5 and I-405 (see Figures 20 and 21). All these routes except Santiago Canyon are equipped with vehicle traffic detection stations (VDSs) and the traffic data are recorded in PeMS. Parts of highways SR133, SR241 and SR261 were closed by the California Highway Patrol as soon as the fire spread on 26 October 2020. Therefore, only the traffic data from the Freeways I-5 and I-405 were available during the evacuation. The time of road closures is listed in Table 10. Most of the closures were in Irvine, and I-5 and I-405 remained open during this event. All road closures were lifted by 5:00 am on 2 November 2020.

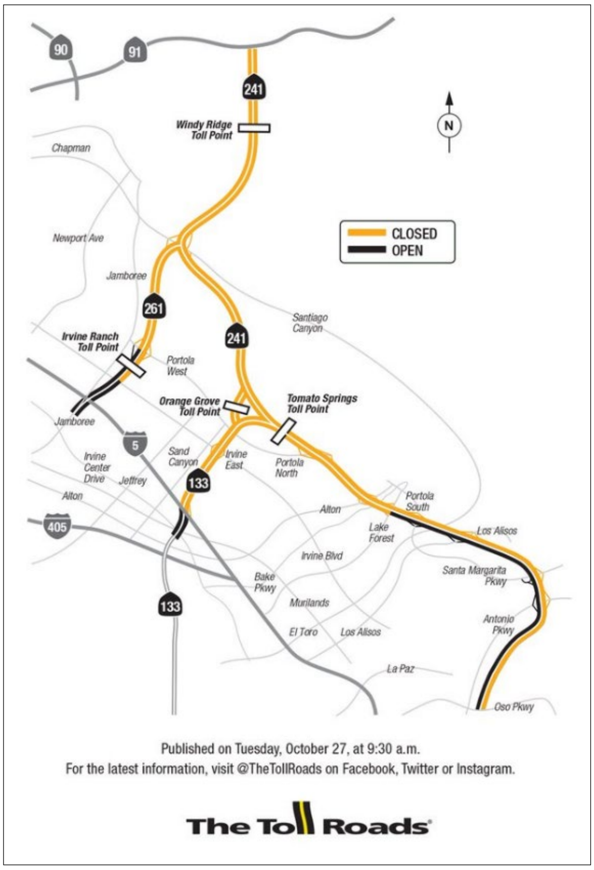

Figure 22. Map of the road closures during the Silverado fire on 27 October 2020 by the Transportation Corridor Agencies (TCA) released on Twitter[13].

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13 https://www.latimes.com/california/story/2020-10-27/orange-county-fires-evacuation-areas-road-and-school-closures-shelters

Figure 22 shows a map of road closures on 27 October 2020 released by Transportation Corridor Agencies (TCA). Since Freeway I-5 is closer to the evacuated areas, equipped with several detectors, and provides access across the evacuation zones, it was chosen as a source to extract PeMS traffic data. Freeway I-5 has 4 to 7 lanes, including High Occupancy Vehicle lanes, depending on the segment location along the freeway. The speed limit of I-5 in urban settings is 65 mi/h (~105 km/h) with 4 to 6 lanes; and in rural settings, the speed limit is 70 mi/h (113 km/h) with a maximum of 7 lanes. Table 11 shows the road specifications of Freeway I-5 in rural and urban settings.

Table 10. List of the road closures during the Silverado fire.

Road Name	**Time**	
	Northbound	Southbound
SR 241	26 till 28 October 2020	26 till 28 October 2020
SR 133	26 till 28 October 2020	
SR 261	26 till 28 October 2020	
Santiago Canyon Rd	26 till 28 October 2020	26 till 28 October 2020

Table 11. Highway I-5 roadway information from PeMS and OpenStreetMap.

Specification	**Rural setting**	**Urban setting**
Maximum number of lanes (-)	7	6
Number of High Occupancy Vehicle lanes (-)	1	1
Speed limit for passenger cars (km/h)	113	105
Speed limit for heavy goods vehicles (km/h)	89	89
Lane width (m)	3.66	3.66
Road width (m)	25.62	21.96
Outer shoulder width (m)	2.44	3.6
Median width (m)	12.3	9.4
Median type	Paved	Paved
Road surface material	Concrete	Asphalt
Location of segment	L1S (see Figure 23)	L5N (see Figure 23)

5.2.2. 2020 Silverado Fire data selection

As explained earlier, we chose Freeway I-5 to extract traffic data for the study. The VDSs (detectors) were selected based on the procedure explained in the previous section. There are 717 vehicle detector stations (VDS) along Freeway I-5 in Orange County, 201 of which use double loop detectors. The selection process (see Table 12) resulted in selecting 18 VDSs for both directions (L1 to L9 for each direction, Northbound and Southbound).

A visual inspection of detectors also accompanied this process to select the best set that met our criteria. The longitude and latitude of each detector were derived from PeMS and overlayed onto a map of the Silverado fire location and evacuation warning and order zones (as shown in Figure 23 and Table 13).

Table 12. Selection process for VDSs in Orange County at the time of the fire event (Freeway I-5).

Highway Name →	**All VDSs** →	**Mainline VDSs** →	**Dual Loop sensor (measuring speed)** →	**Health>97%** →	**Distance threshold**
I-5	704	236	201	148	18

Table 13. Location, milepost, and ID of the selected VDSs on the northbound and southbound segments of highway I-5 (as shown in Figure 23).

Northbound			**Southbound**		
Location	**Milepost (mi)**	**VDS ID**	**Location**	**Milepost (mi)**	**VDS ID**
L1N	84.518	1211107	L1S	84.105	1204458
L2N	85.308	1204472	L2S	89.455	1204565
L3N	89.888	1204586	L3S	90.895	1204621
L4N	92.258	1204672	L4S	93.145	1204701
L5N	96.308	1204861	L5S	95.885	1204841
L6N	97.338	1204924	L6S	97.035	1204904
L7N	98.818	1204982	L7S	100.288	1205105
L8N	101.491	1205135	L8S	103.088	1205182
L9N	103.051	1205175	L9S	104.088	1205230

The traffic data was extracted from three different time intervals including evacuation and routine time periods (as shown in Table 14) for all lanes by means of the TDA (Traffic Dynamics Analyser) tool created by Rohaert et al. (2022). Since most population movements occurred on the 26th and 27th of October, these two days were considered as the evacuation period. Similar days were selected one week and two weeks before the fire to compare traffic data during routine and evacuation conditions. The data has been extracted, processed and released through the Open Access platform and is available for the research communities (Janfeshanaraghi et al., 2023).

We also calculated the average health (percentage) of the selected VDSs from the PeMS database in the above-mentioned time intervals (see Table 15). It should be noted that each VDS (e.g., L1N or L1S) includes multiple detectors (one detector per lane). Table 15 shows good health conditions for all VDSs (most more than 95%), as it has been a critical criterion in the selection process. Besides detector data, the PeMS database also contains incident reports from California Highway Patrol (CHP). Appendix 1 summarize the reported incidents on Freeway I-5 from mileposts 84 to 105 within the impacted area in Orange County, CA. No injuries or fatalities were reported in any of the incidents.

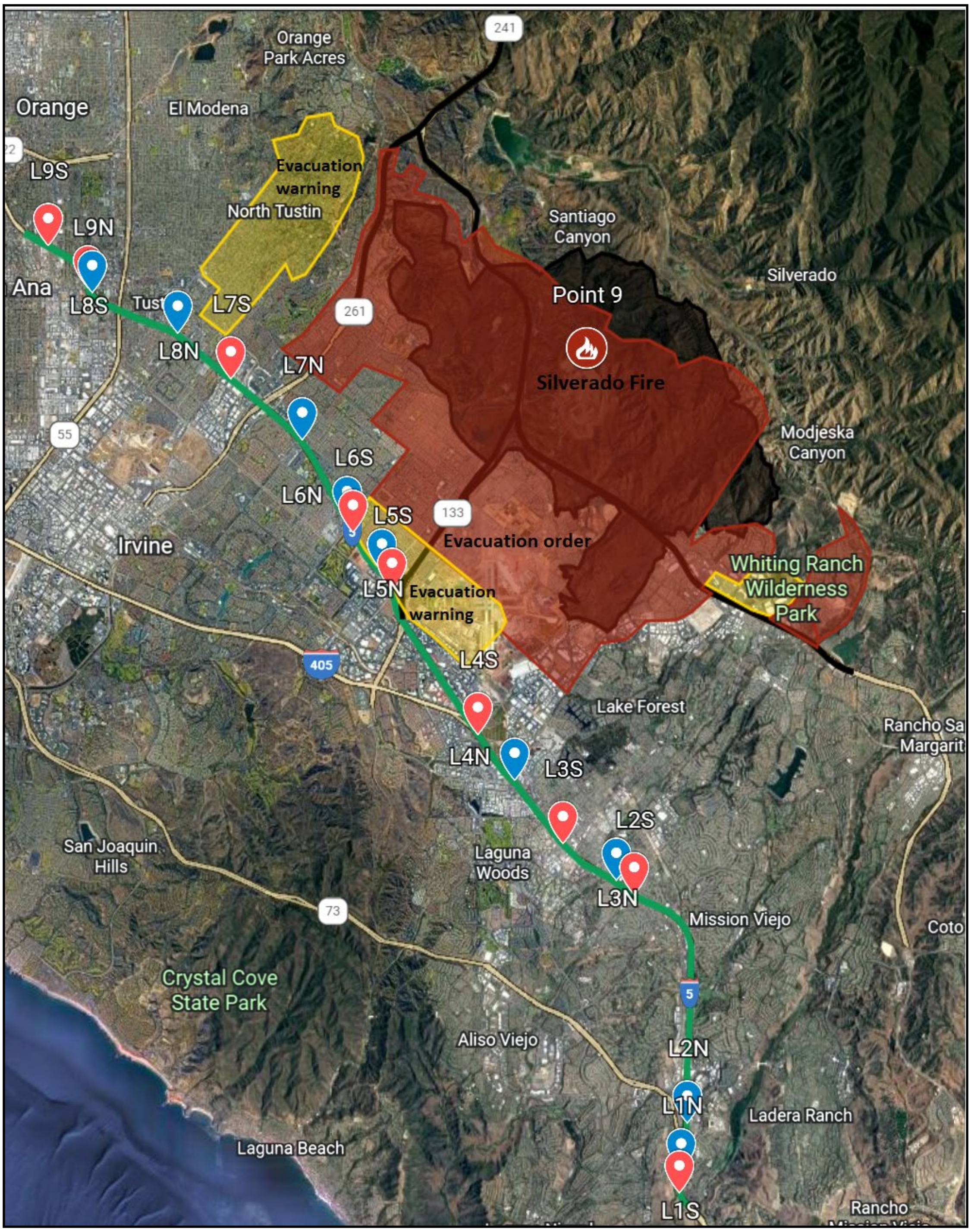


Figure 23. Map with the location of the selected VDSs (detectors, coordinates source from PeMS), the 2020 Silverado wildfire perimeter and the evacuation warning and order zones at the time of fire (Orange County, City of Irvine, and City of Lake Forest). Road closures are presented by dark lines for the SR241, SR133, SR261. Figure created based on Google Map with overlayed areas and markers (blue markers: Northbound detectors, red markers: Southbound detectors) by the authors. Red polygons indicate the evacuation order zones and yellow polygons indicate the evacuation warning zones.

The most frequent incidents during the evacuation time period (26 and 27 October) were traffic hazards, as seen in Appendix 1. In addition, an incident (CFIRE-Car Fire) in the early hours (at

2:49 am) on Tuesday, 27 October, caused a traffic jam for 207 minutes southbound of Freeway I-5 (this incident is explained in the following sections).

Table 14. Time periods of data extraction for the Silverado fire (October 2020).

Time interval	**Abbreviation**	**Start (Monday)**	**End (Tuesday)**
		October 2020	
Two weeks before (routine)	R1	the 12th	the 13th
One week before (routine)	R2	the 19th	the 20th
Evacuation	E	the 26th	the 27th

Table 15. Health of the detectors (%) during different time intervals of data extraction.

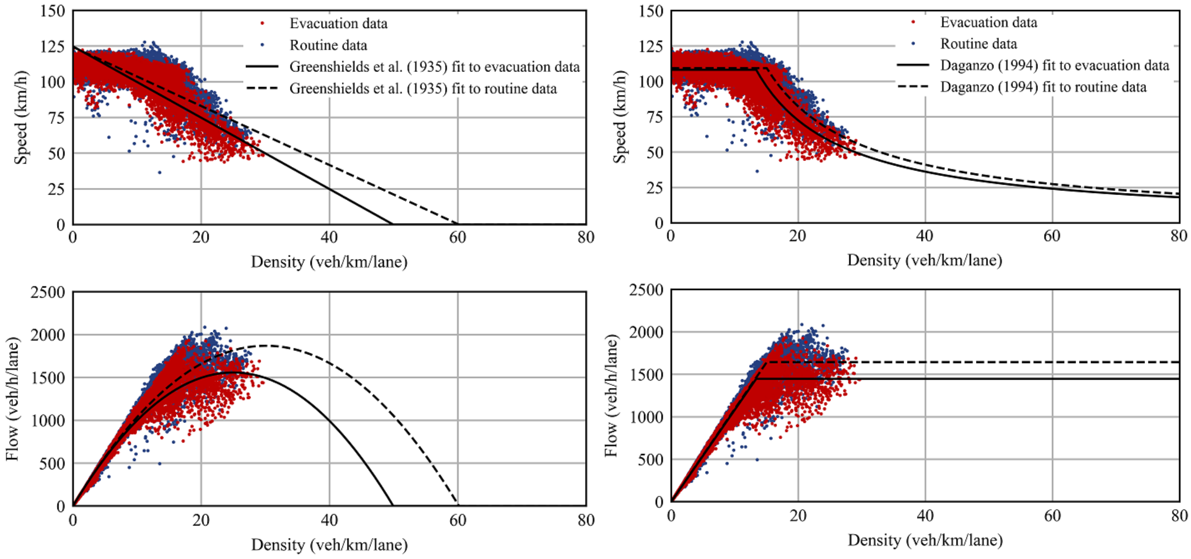
Time interval	L1N	L2N	L3N	L4N	L5N	L6N	L7N	L8N	L9N
R1	100	100	100	100	100	100	90	100	99.7
R2	100	100	100	89.4	100	100	80	99.6	99
E	100	100	100	99.8	100	100	100	99.1	99.3
Time interval	L1S	L2S	L3S	L4S	L5S	L6S	L7S	L8S	L9S
R1	98.9	100	99.6	100	100	100	100	100	100
R2	99.2	100	100	95.5	100	100	100	100	100
E	99.2	100	100	100	99.5	100	100	100	100

5.2.3. 2020 Silverado Fire data analysis

To analyse traffic data from the Silverado fire, curves were fitted to the fundamental diagrams; The best fitted models and their related parameters and optimal values are shown in Table 16. Since most of the data fall within the range of 0 to 30 (veh/km/lane, v/km/l), and there are only 19 data points where the density is greater than 30 v/km/l in routine conditions, the curves were optimized to fit well within this range. In Figures 24-26, the evacuation data (E) and routine data (R1+R2) are shown in the speed-density and flow-density graphs for the selected models.

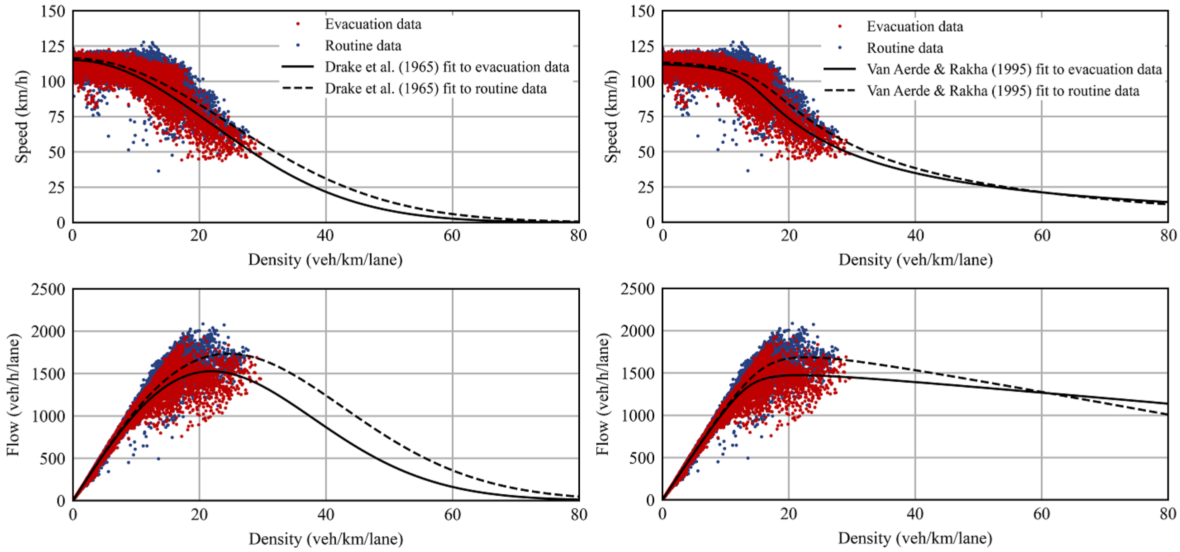
Table 16. Fitted macroscopic traffic models to the 2020 Silverado fire evacuation traffic data (Freeway I-5), related parameters and best fit value.

Model	Relationship	Parameters and best fit value (E)	Parameters and best fit value (R1+R2)
Daganzo, (1994)	$v = \begin{cases} v_f, & 0 \le k \le k_c \\ v_f \dfrac{\left(\frac{1}{k} - \frac{1}{k_j}\right)}{\left(\frac{1}{k_c} - \frac{1}{k_j}\right)}, & k_c \le k \le k_j \end{cases}$	WRMSE = 7.65 v_f = 108.20 km/h k_c = 13.37 v/km/l k_j = 1.37E+08 v/km/l	WRMSE = 6.77 v_f = 109.34 km/h k_c = 15.03 v/km/l k_j = 2.69E+08 v/km/l
Greenshields (1936)	$v = v_f\left(1 - \dfrac{k}{k_j}\right)$	WRMSE = 8.79 v_f = 124.83 km/h k_j = 49.94 v/km/l	WRMSE = 8.012 v_f = 124.34 km/h k_j = 60.17 v/km/l
Drake et al., (1967)	$v = v_f e^{\left(-\frac{1}{2}\left(\frac{k}{k_c}\right)^2\right)}$	WRMSE = 7.63 v_f = 115.04 km/h k_c = 21.89 v/km/l	WRMSE = 6.54 v_f = 116.27 km/h k_c = 24.61 v/km/l
Van Aerde and Rakha, (1995)	$k = \dfrac{1}{a + \dfrac{b}{v_f - v} + c\,v}$ with $\begin{Bmatrix} a = v_f(2v_c - v_f)/k_j v_c^2 \\ b = v_f(v_c - v_f)^2/k_j v_c^2 \\ c = 1/(v_c k_c) - v_f/k_j v_c^2 \end{Bmatrix}$	WRMSE = 7.16 v_f = 111.96 km/h a = 2.33E-03 b = 1.84E-01 c = 5.83E-04	WRMSE = 6.12 v_f = 113.34 km/h a = 4.66E-03 b = 2.08E-01 c = 4.59E-04
Cheng et al. (2021)	$v = \dfrac{v_f}{(1 + (k/k_c)^m)^{2/m}}$	WRMSE = 7.36 v_f = 112.4 km/h k_c = 20.94 v/km/l m = 3.10	WRMSE = 6.19 v_f = 112.63 km/h k_c = 22.38 v/km/l m = 3.52
Highway Capacity Manual (2016)	$v = \begin{cases} v_f, & 0 \le k \le k_b \\ v_f - (v_f - v_c)\left(\dfrac{q - q_b}{q_c - q_b}\right)^a, & k_b \le k \le k_c \\ \dfrac{q_c}{k_j}\dfrac{q}{q_c - q}, & k_c \le k \le k_j \end{cases}$	WRMSE = 7.77 v_f = 108.82 km/h k_c = 12.45 v/km/l k_j = 24821.42 v/km/l q_b = 1741.25 q_c = 1428.29 a = -8.38	WRMSE = 6.08 v_f = 113.10 km/h k_c = 16.72 v/km/l k_j = 27594.88 v/km/l q_b = 581.83 q_c = 1660.42 a = 1.14



(a) (b)

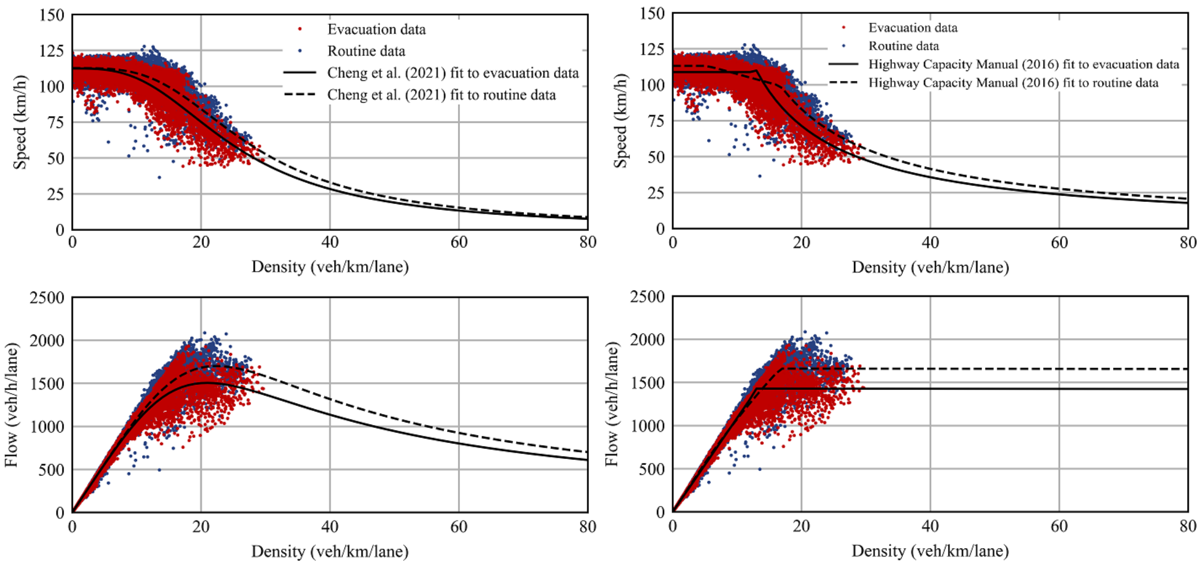
Figure 24. Speed-density and flow-density diagrams for the evacuation data (E) and routine data (R1+R2) and best-fit curves (a: Greenshields et al. (1935), b: Daganzo et al. (1994)).



(a) (b)

Figure 25. Speed-density and flow-density diagrams for the evacuation data (E) and routine data (R1+R2) and best-fit curves (a: Drake et al. (1967), b: Van Aerde & Rakha et al. (1995)).

Six models were selected to fit the traffic data. As shown in Figures 24-26, most of the data points in the evacuation and routine conditions fall within the low-density region. These figures indicate that the Greenshields model poorly fits. In contrast, the model by Van Aerde and Rakha and the model by Cheng and Daganzo offer a better fit since they use additional parameters to improve the fit. Table 16 also provides the WRMSE for all models. A lower value for WRMSE indicates a better fit. Based on the WRMSE, it can be seen that the HCM model provides a better fit for the routine data, when compared with the evacuation data.



(a) *(b)*

Figure 26. Speed-density and flow-density diagrams for the evacuation data (E) and routine data (R1+R2) and best-fit curves (a: Cheng et al., (2021), b: HCM, (2016)).

Flow-density and speed-density relationships during routine and evacuation traffic are depicted in Figure 27 (a and b). The diagrams show that generally there is an insufficient number of data points in the high-density traffic region (i.e., only 19 data points greater than 30 veh/km/lane). However, for density values between 10 to 30 veh/km/lane, the speed and flow of traffic are slightly lower during the evacuation scenario, when compared with routine conditions.

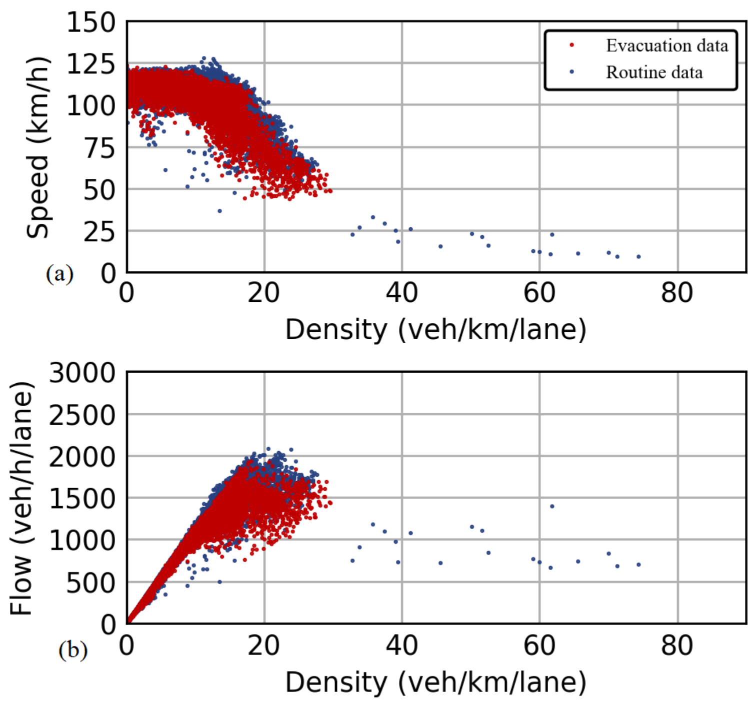


Figure 27. a: Speed-density and b: Flow-density diagrams for the evacuation data (E) and the routine data (R1+R2)

The average traffic flow of all selected VDSs on Freeway I-5 before, during and after the fire event is shown in Figure 28. This figure compares the traffic flows during the fire event (week

44) with those recorded during the nine weeks preceding the fire (week 35, which started on 24 August until the end of week 43; i.e., 25 October) and the two weeks after the fire event (week 45, which started on 2 November until the end of week 46; i.e., 15 November). This entire period is within the school season (which began on 18 August). Therefore, the school summer breaks were not considered as a factor affecting the traffic patterns during our selected time period. Labour Day (7 September), a national holiday in the United States, is excluded from this calculation due to its significantly lower traffic volume. Table 17 also shows the average daily traffic flow at different times within the period of data extraction.

The Silverado Fire started on Monday, 26 October. The first evacuation order was issued in the morning of 26 October and evacuation warnings and orders continued to be issued until later into the night of that same day. Over the course of the event, it was estimated that 90,000 people had been ordered to evacuate from Orange County. Based on Figure 28, traffic volumes on Monday and Tuesday (26^{th} and 27^{th} of October, i.e., week 44) were lower than the average of the nine weeks prior to the fire. The average daily traffic flow also shows this pattern with a volume decrease of at least 4% during the evacuation compared with routine conditions (see Table 17). This reduction in volume and flow aligns with the recent study by Rohaert et al. (2022) for the Kincade fire, in which lower traffic volumes were observed when mandatory evacuation was ordered. All evacuation warnings and orders were lifted in the city of Irvine and Lake Forest on Wednesday and Thursday (28 and 29 October). Figure 28 shows that traffic flow on I-5 was higher on Wednesday (28 October, week 44) until Friday (30 October, week 44), when compared to the average nine-week traffic flow (before the fire started). This unusual traffic volume increase compared with the average nine weeks before can be related to lifting evacuation orders and people returning to their homes. It also could be related to road closures during these periods. Road closures can temporarily increase the traffic volume on other routes. Normal traffic conditions were observed on Saturday and Sunday (31 October and 1 November) at the end of week 44.

Two weeks (i.e., week 45 and 46) were selected to observe the traffic flow condition after the fire event. Both weeks show similar traffic conditions compared to the weekdays' nine-week average traffic flow. Lower traffic flow was observed during the weekend of week 45 and was not observed the following weekend (week 46). The decrease in traffic volume during the weekend of week 45 may be related to weather and subsequent traffic incidents on roadways since weather conditions can influence drivers’ decisions and behaviour (Kilpeläinen & Summala, 2007; Ahmed & Ghasemzadeh, 2018; Bakhshi et al., 2022). The incident report from the California Highway Patrol, which is accessible in the PeMS database, shows that on 7 November 2020, there was heavy rain resulting in a flood on the roadway of Freeway I-5 that resulted in some accidents.

Table 17. Average traffic flow during different time intervals of data extraction.

Scenario	**Start**	**End**	**Average traffic flow (veh/day)**
	(October 2020)		
Routine (R1)	the 12th	the 13th	110 235
Routine (R2)	the 19th	the 20th	111 071
Evacuation (E)	the 26th	the 27th	105 707
Routine (one week after fire)	(November 2020)		108 815
	the 2^{nd}	the 3^{rd}	

We also analysed the parameter Q, defined as a measure of the efficiency of the transportation system for a freeway segment over time (Caltrans, 2020; Chen, 2003b). It is also known as the space mean speed (or weighted harmonic mean of detector speeds on the freeway).

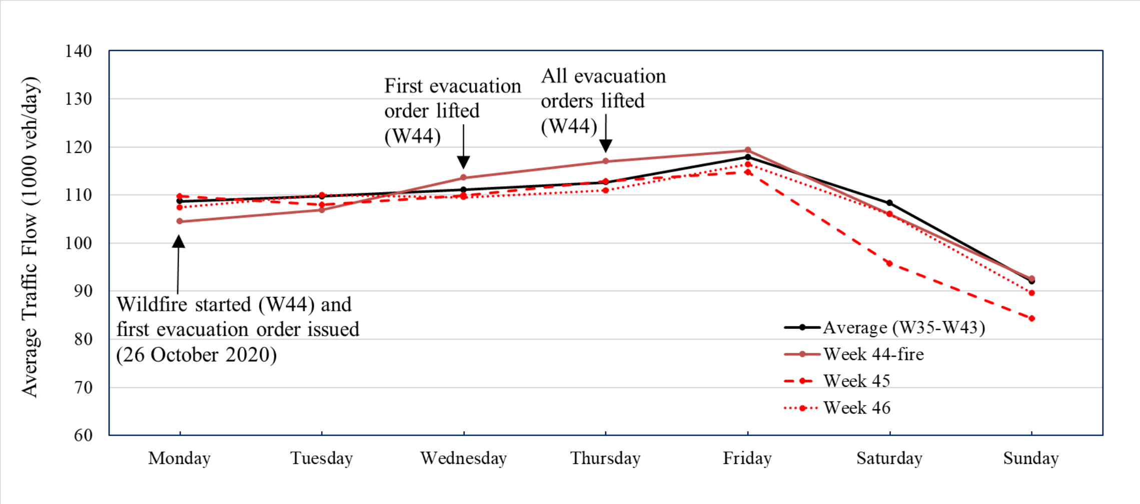


Figure 28. Average traffic flow before, during, and after the Silverado fire.

Q is calculated by dividing Vehicle Miles Travelled (VMT) by Vehicle Hours Travelled (VHT). In a freeway segment, VMT represents the total miles driven by all vehicles over a specified time, and VHT represents the total time spent by all vehicles over the same segment. Figures 29 and 30 show this value over time for the three time periods of data extraction (evacuation and the two routine time periods) and the segment that covers all the selected detectors starting from milepost 84 to milepost 105 within the fire-impacted areas (see Figure 23 and Table 13). As mentioned earlier, the first evacuation order was issued on Monday morning, 26 October. These figures indicate that, due to traffic congestion on Freeway I-5 during the evacuation time, the mean speed (Q) decreased by a maximum of 22% for northbound and 25% for southbound, compared with the routine conditions. Also, a higher reduction of mean speed by 50% (52.46 km/h at 2:00 am), compared with the routine conditions, is seen on the I-5 southbound segment early on Tuesday, 27 October. After review of the incidents that occurred during this time and on this segment of the freeway (Table 16), this reduction in speed was likely due to an incident (i.e., the car fire), which resulted in traffic congestion in the southbound direction of I-5.

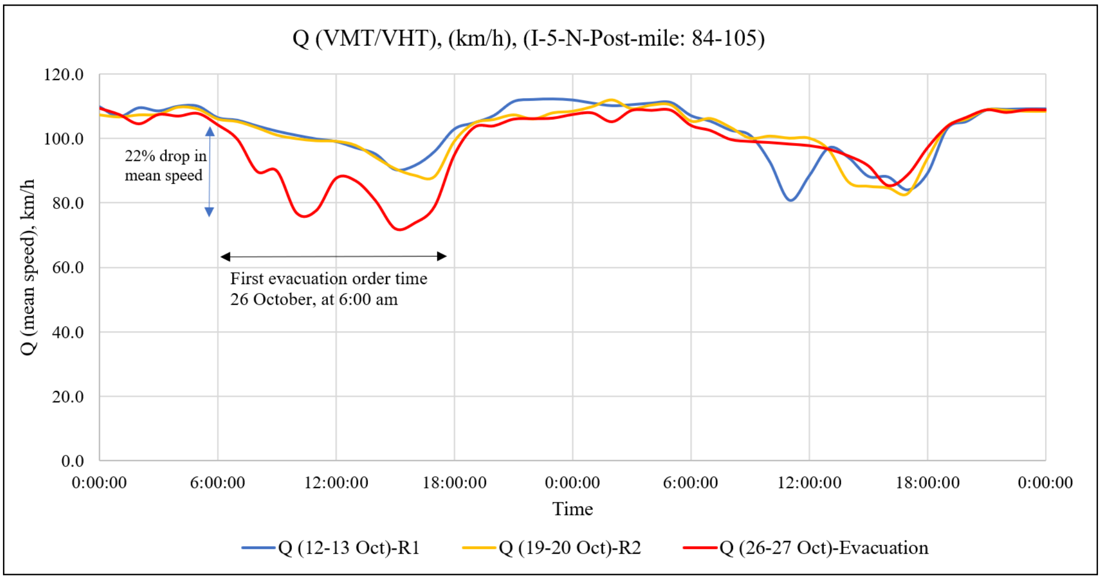


Figure 29. Analysing Q in different times of data extraction on I-5-Northbound.

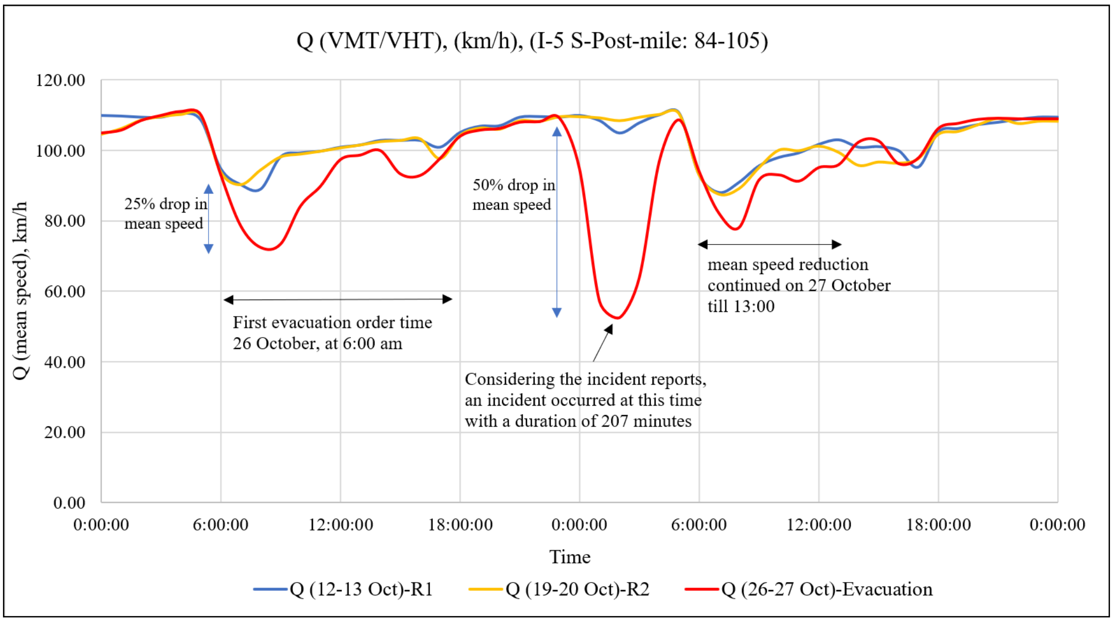


Figure 30. Analysing Q in different times of data extraction on I-5-Southbound.

To summarize, traffic data from PeMS was extracted to analyse evacuation from the 2020 Silverado fire. Six models were fit to the traffic data for both routine and evacuation conditions; given the lack of data in the higher density regions, there is a need for further research into fires with varied traffic dynamics, fire, population, and built environmental conditions. Generally, this case study highlighted that traffic moved slightly slower during evacuation scenarios when compared with routine traffic conditions. Additional temporal analysis of the data showed that traffic volumes and flow were lower during the two days that evacuation orders and warnings were issued (Monday and Tuesday) when compared with traffic data before and after the fire. In fact, the traffic volume decreased on freeway I-5 for the two days of evacuation warnings and orders (Monday and Tuesday) and increased on Wednesday and Thursday when the warnings and orders were lifted. This result aligns with previous research conducted on another fire studied in California (Rohaert et al., 2022), and is likely due to the issuance of evacuation warnings and orders during the first day of the fire, location of the detectors under consideration in relation to the fire and road closures causing an increase in traffic volume during re-entry processes.

6. VR for the study of driving behaviour in wildfires

This section of the report describes the development and initial evaluation of a virtual reality (VR) driving simulation scenario for the purpose of studying evacuee decision-making and behaviour. It is hoped that this approach can generate fine grained behavioural data that is immediately relevant for the WUI-NITY tool (e.g., input to the traffic simulation component).

Gathering empirical data on human behaviour during WUI fire evacuations are challenging. In particular data on individuals' decision-making (e.g., when and how to evacuate, on the fly routing decisions while in traffic, driving adjustments to traffic and environmental conditions, etc.) are challenging to study in controlled, safe, and valid manners. However, VR allows for the testing of behavioural hypotheses in emergency scenarios without exposing people to the risks of an actual wildfire (Kinateder, Ronchi, Nilsson, et al., 2014). VR allows high-fidelity simulation of the scenario in a way that is safe, ecologically valid for certain decisions in given scenarios, and cost-efficient. The usefulness of VR as a research tool in the context of building fire evacuation has been confirmed in a range of studies (e.g., (Kinateder & Warren, 2016)). A first attempt to study individual driving behaviour in VR during wildfire evacuation scenarios showed that reduced visibility conditions (see Figure 31) contributed to a decrease in driving speed (Wetterberg et al., 2020). Many other open questions remain, however. For instance, it is currently unclear how other environment variables (e.g., embers, traffic congestion, signage, route guidance) would affect driving with and without the presence of smoke.

Very few studies have examined the use of VR in the context of evacuee behaviour and decision-making during wildfire evacuations. Most studies published to date have used VR in the context of building (Andrée et al., 2016; Arias et al., 2022; Cao et al., 2019; Zhang et al., 2021) and road tunnel fire evacuations (Kinateder, Ronchi, Gromer, et al., 2014; Kinateder, Müller, et al., 2014; Ronchi, Nilsson, Kojić, et al., 2016) and wildfire training for firefighters (Heyao & Tetsuro, 2022).

One study explored the predictors of intention of early evacuation from a wildfire (i.e., risk perception, protective action perception, and stakeholder perceptions) and how exposure to a VR scenario would impact participants' decision to leave early. In the VR scenario, a series of scenes with various social (e.g., evacuating neighbours) and environmental cues (e.g., smoke) were presented to participants. After each scene, participants were asked about the perceived risk of the wildfire and how likely they were to leave at this time. The longer participants decided to stay, the more hazardous the situation became (Molan et al., 2022). Although this study helped to raise awareness about the consequences of delaying evacuation, it did not examine behaviour during a wildfire evacuation per se.

Figure 31. Screenshot from a driving behaviour task in VR performed at Lund University during wildfire evacuation in presence of smoke (optical density is equal to 0.5 m^{-1} in this example). Figure taken from (Wetterberg et al., 2020).

This part of the project aims at building the foundations to use VR simulations for research on wildfire evacuations, particularly in the WUI. This will allow research on evacuee behaviour under the conditions outlined above in a Canadian context that can be later on extrapolated to different contexts. Specifically, VR technology is used to study traffic evacuation movement variables which we cannot systematically investigate from existing traffic databases (e.g., interaction with embers/smoke). The goal is to use this approach to complement other modes of data collection given the implausibility of performing traditional experiments exploring key unknowns.

6.1. Scenario identification

The research team chose to base the VR scenarios on the Fort McMurray (province of Alberta, Canada) wildfire as it is one of the largest wildfire evacuations in Canadian history and worldwide and is also well documented. The wildfire was spotted on May 1, 2016 in the Wood Buffalo area near Fort McMurray. Over 125,000 people lived in the area. Strong winds and elevated temperatures promoted the development of the fire. On May 3, the fire entered Fort McMurray and led to the evacuation of over 60,000 residents by the end of the day. The fire continued spreading over the next few days and thousands more residents were instructed to evacuate. The province also declared a provincial state of emergency. Eventually, more than 88,000 residents were evacuated with two fatalities due to a vehicle crash (Woo et al., 2017).

Since many residents evacuated via a private vehicle or other mode of transportation (e.g., buses) during wildfires, the research team decided to focus on driving scenarios. Following a literature review, the research team created a list of requirements for the VR driving scenarios, such as environmental conditions/visual effects, traffic conditions, appearance of the interior of the driver cabin, user interface, road signage, etc. Based on the requirements, the Design and Fabrication Service (DFS) at the NRC developed two virtual environments. Both model the real-world Fort McMurray area, with some differences (e.g., commercial buildings are based on those seen in Google Streetview, but they are not exact replicas of the real-world buildings).

The first virtual environment developed represents a "blue sky" scenario (i.e., no wildfire, except for a plume of smoke seen in the distance, see Figure 32). The second virtual environment is a "wildfire" scenario (see Figure 32) and is identical to the first environment, except that it contains visual effects related to wildfires (e.g., haze/fog, ember showers). In both virtual environments, an ad hoc artificial intelligence (AI) traffic system with a broad range of vehicles (e.g., trucks, sedans) was implemented, which the user can activate or deactivate (e.g., if a scenario does not require traffic, the feature can be deactivated).

The virtual environment can be flexibly adjusted for potential future scenario, including several elements that can be manipulated. These include, varying environmental conditions (e.g., ember showers, fog/haze, with ability to manipulate density) in the "wildfire" scenario. Furthermore, the traffic system will be refined (e.g., ability to manipulate the route of an individual AI vehicle relative to the user's position, fine-tuning the AI vehicles' behaviour) and a night scene is being generated for both virtual environments. These additions will allow to explore research questions related to traffic and environmental conditions, such as the effect of lower or higher visibility on evacuee driving behaviour during a wildfire evacuation.

In addition to the VR scenarios, the research team developed a study protocol that describes the objective and methods of the first pilot data collection (e.g., number and characteristics of research participants, measures and equipment used, task for research participants). The research team also developed an experiment framework in Unity, which allows the implementation of controlled within and between subject studies, data recording, and practice scenarios (to let participants learn how to interact with the environment) for research studies.

6.2. Scenario Development

Two virtual environments were developed in Unity (version 2020.3.14f1), a cross-platform game engine that allows to create 2D and 3D games and experiences (https://unity.com/)[14]. One benefit of using Unity includes being able to edit visual aspects and integrate code within the same environment. In addition, developers can use Unity's Asset Store to download assets (e.g., 3D vehicles, characters, animations) created and shared by other developers instead of creating them from scratch (https://assetstore.unity.com/)[14].

The "blue sky" scenario was developed first. The first step was to generate the terrain and road network of Fort McMurray. The total size of the terrain (map) is approximately 64 km^2. then placed objects in the virtual environment and implemented the traffic system, the player car, and the user interface. Once the basic "blue sky" scenario was complete, they began developing the "wildfire" scenario by including various environmental conditions related to wildfires. Additional details are provided below.

6.2.1. Terrain

Gaia Pro 2021 - Terrain & Scene Generator (an asset in the Unity ecosystem; Procedural Worlds) was used to create terrain tiles (terrain is represented in rectangular tiles in the Unity environment). This asset was chosen due to its capability to produce high-quality terrains quickly, its relative ease of use, its high customizability, and its built-in terrain management capabilities. High-resolution satellite maps of Fort McMurray were obtained from Natural Resources Canada (see https://open.canada.ca/data/en/dataset/957782bf-847c-4644-a757-e383c0057995)[14], transferred into Photoshop for use with Gaia Pro in Unity and converted into stamps. The resulting terrain stamps were used to shape Unity's special terrain geometry objects to reproduce the geography of Fort McMurray in the areas that were deemed to be of high importance (the centre of Fort McMurray and the area along Memorial Drive leading to the planned evacuation site in Gregoire, Alberta). Lower resolution heightmaps for areas further away from the evacuation route were obtained from the internet (heightmap.skydark.pl)[14]. The terrain geography was lightly manipulated in Unity to smooth out imperfections, level the ground between different terrain tiles and flatten the ground to facilitate the placement of roads and buildings. Care was taken not to fundamentally alter the geography.

6.2.2. Road Network

GeNa Pro (a Unity asset and add-on to Gaia Pro; Procedural Worlds) to procedurally generate the road network. This asset was chosen as it is fully integrated with Gaia Pro. Satellite imagery of the Fort McMurray road network was superimposed over the terrain in Unity and the roads were laid on top. Major roads had to be reduced to simple two-lane roads because GeNa cannot create complex four-lane roads with elements such as centre dividers, slip lanes, merging or turning lanes, etc. This also reduces the number of potential confounding factors because if four-lane roads were implemented, it would be difficult to determine whether a user's driving behaviour is due to the variable being studied (e.g., messages on road signs) or to other variables (e.g., traffic in the next lane). Some small roads, dead-ends, and roads far from the planned evacuation route were omitted for simplicity.

[14] Last website access during the report writing on the 14/04/2023

6.2.3. *Object Placement*

Several different types of residential, commercial, and light industrial buildings were created; the buildings were based on the types of buildings seen while exploring Fort McMurray in virtually using Google Streetview. Buildings were placed on the map based loosely on what was observed in Streetview (houses in residential areas, shops in commercial areas, warehouses in industrial areas). A few notable landmarks were reproduced and placed appropriately. However, the goal was not to create an exact replica but rather a simplified model resembling Fort McMurray.

6.2.4. *AI Traffic System*

Simple Traffic System (STS; a Unity asset to create waypoint based routes on roads; TurnTheGameOn) was used to manage the AI traffic system and create routes the non-player vehicles would follow as well as the stop and traffic light systems at intersections. This asset was chosen to for its simplicity and ease of implementation. A more refined traffic system can be implemented in further iterations. Using Simple Traffic System tools, AI routes were drawn over the road network and linked together to allow AI vehicles to navigate the entire city. Intersections were configured as two-, three-, or four-way stops or with traffic lights as needed. Simple Traffic System handles the spawning (appearance) and despawning (removal) of vehicles to keep their numbers within an acceptable range to avoid performance issues from having too many vehicles in the scenario. It also ensures AI vehicles spawn outside the player's visual range. AI vehicles themselves were from a vehicle library. The user can control the total number and density of vehicles in the virtual environment as well as the number of vehicles spawned in a particular zone (the zone can be enlarged or reduced in size). The user can also assign which vehicle type (e.g., sedan) is allowed on a particular route, set the speed limit for a particular route and the speed of specific vehicle types, the steer sensitivity, the maximum steering angle, and other features via the AI Traffic Controller in Unity.

6.2.5. *Player Car*

A custom vehicle with a detailed driver cabin was created, based on the appearance of a Toyota Corolla; this make and model were chosen since they can be commonly found on Canadian roads[15]. Vehicle Physics Pro Community Edition (VPP, unity asset) was used to implement the physics of the player car (i.e., the vehicle that research participants would use). This asset was chosen due to its highly-customizable vehicle physics package. It has a built-in user interface for the dashboard instruments, sound effects, and handles the driving and physics logic. The user can control many vehicle dynamics via the Vehicle Controller in Unity, such as the vehicle's steering (Ackerman, TOE, multiple steering axles), brakes (front, rear, neutral, handbrake, retarder), tire friction (Flat, Linear, Smooth, Parametric, Pacejka), engine (torque curve, brake torque, fuel consumption, stall), etc. For additional features, see https://vehiclephysics.com/about/features/. The Vehicle Physics Pro user inputs (i.e., the inputs from the person steering the virtual car) were mapped to a Thrustmaster 300GT steering wheel and pedals.

6.2.6. *Wildfire Environmental Conditions*

Several visual effects related to wildfires, such as haze/fog, smoke, and ember showers were created (see Figure 32). These were based on image and video material of wildfire evacuations from Fort McMurray and other places. The effects were replicated as accurately as possible in the behaviour and appearance of the environmental conditions in Unity. The haze/fog effects

[15] https://media.toyota.ca/releases/toyota-marks-50-millionth-corolla-sold

were implemented through lighting and rendering settings in Unity. The user can control the fog appearance, such as its colour, density, height, and gradient. Ember showers and smoke effects were created using particle systems in Unity. The user can control several features via the particle system, such as the maximum number of particles spawned, the spawn rate of the particles, and the particles' lifespan.

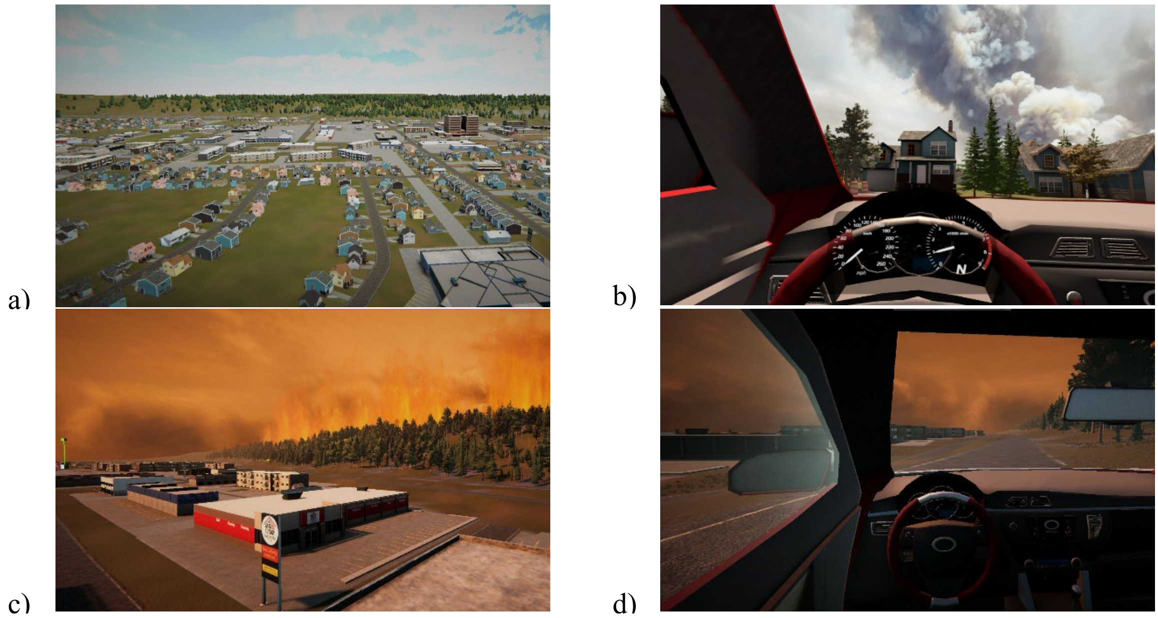


Figure 32. Screenshots of the virtual environments. a) "blue sky scenario"; b) first person view from inside the vehicle in the "blue sky" scenario with smoke sky box; c) "wildfire" scenario; d) first person view from inside the participant's vehicle in "wildfire" scenario.

6.3. Virtual Reality Prototype Development

Users are immersed in the driving scenario via a Vive Pro head-mounted display (https://www.vive.com/ca/product/vive-pro/). They navigate in the scenarios via a Thrustmaster 300RS steering wheel and acceleration and brake floor pedals (https://www.thrustmaster.com/en-gb/products/t300rs/).

As part of the development process, the research team did some internal piloting of the "blue sky" scenario. They drove through the virtual environment and provided feedback on the user interface, object placement, traffic system, etc.; the scenario was refined based on this input. For example, following initial testing, a mini map was developed of the virtual environment to help users navigate (see Figure 33).

Figure 33. Overview of the developed virtual environment; this illustration is also used as a mini map.

In addition to the virtual environment a study protocol and a programming framework was developed in Unity for running and collecting data. This will be used in future behavioural studies. The framework provides an experiment structure commonly used in behavioural studies that allows looping through a set of conditions/trials. It can be used to define start and end points of a data collection, data to be logged (e.g., trial duration, user coordinates, events, etc.). The system can generate two types of output files while a user is immersed in the scenario. The first file contains summary data about the trials (e.g., trial state, trial duration). The second one contains more precise trajectory data (e.g., user position, rotation, and timestamps).

6.4. Pilot study on Variable Message Signs during WUI fire evacuation

The research team conducted an exploratory data collection with a small group of participants. The data generated can be used to improve the driving scenario and to further develop a large-scale study of driving behaviour in the future. Participants' general task during the pilot study was to drive through the scenario on a predetermined route.

6.4.1. *Variable Message Signs (VMS)*

For the pilot study data collection, the research team decided to use variable message signs (VMS, also known as dynamic or changeable message signs), which are used to provide information about road conditions and incidents, including traffic congestion or accidents and emergencies. VMS are typically installed permanently or temporarily over highways or on the side of roads.

For example, in Canada, provinces and municipalities use VMS to help direct traffic during wildfires. However, to the best of the authors' knowledge, no studies have yet examined the effect of VMS on drivers' decisions and driving behaviour specifically while evacuating from a wildfire, particularly in low visibility conditions (e.g., smoke, haze, ember showers). A pilot study used a VR driving simulator to explore the effect of VMS on driving behaviour in the context of a wildfire evacuation. Larger studies will investigate the impact of various environmental conditions on driving behaviour.

Previous studies suggest that less than half of drivers will modify their route choice based on traffic congestion information provided by VMS (Erke et al., 2007). However, in the case of wildfire evacuations, drivers must follow instructions provided by authorities or risk endangering themselves and passengers. In addition, many prior studies were conducted using stated preference surveys (e.g., Ma et al., 2014; Spyropoulou & Antoniou, 2015) and/or in countries in Asia (e.g., Kolisetty et al., 2006; Lai, 2008, 2010, 2012), which use a different writing system. However, it is unclear whether this effect would also be observed in the context of wildfires.

Generally, depending on the size of the VMS, it can display the following information during incidents or emergencies: (1) the problem (e.g., accident, traffic congestion), (2) its location (e.g., distance in km or time of driving ahead), and (3) the action that drivers should take (e.g., take caution, leave road). If the VMS is unable to accommodate all three elements, it is recommended to provide information on the action that drivers should take to avoid uncertainty (Dudek, 1991). In addition, drivers tend to react faster to two-line messages than to single- or three-line messages (Lai, 2010). The size of the text should be proportionate to the distance at which it expected to be viewed (Borowsky et al., 2008; Shinar & Vogelzang, 2013). Previous studies also suggest using amber-coloured text on a black background to enhance the visibility of the sign (Wang et al., 2006). In addition, including pictograms or symbols (when drivers are familiar with them) on VMS can help drivers better understand and remember the information displayed (e.g., Wang & Cao, 2003). A light in each corner of the VMS flashing in synchrony can also be useful to attract participants' attention (Nilsson et al., 2009; Ronchi, Nilsson, Modig, et al., 2016). The design of the VMS used in the current pilot study is based on these findings.

Objectives

The main purpose of the pilot study was to explore the usability of the driving simulator, whether there were specific components of the VR driving scenario that participants preferred, and whether participants thought there were any improvements or adjustments that should be made to the scenario, the measures used, and/or the study protocol.

Subjective/qualitative data were collected (questionnaire responses and open-ended feedback) that will inform the experimental design of larger studies and help improve the driving scenario. Specifically, the pilot study explored potential research avenues/experimental manipulations for larger studies.

In addition, the pilot study examined individual driving behaviour when different messages were displayed on a VMS during a simulated evacuation. For the purpose of the pilot study, the directions indicated by the VMS (either follow a detour to the left or right), as well as the length of the message were manipulated. Participants' driving trajectory was observed and recorded.

Methods

The pilot study had one independent variable (i.e., experimental/VMS conditions) and two dependent variables (i.e., participants' experience and their driving behaviour).

Participants first completed a practice trial to familiarize themselves with the driving simulator and the virtual environment. The practice trial was followed by a total of five control and experimental trials in a randomly assigned order: (1) Control, (2) VMS right short message, (3) VMS left short message, (4) VMS right long message, and (5) VMS left long message. See Figure 34 for screenshots of the messages displayed on the VMS in each condition.

The pilot study followed a within-subjects design as it required a smaller number of participants compared to a between subjects-design, and learning effects should be minimal as the previous trial should not impact driving behaviour in the next trial (e.g., the message in the practice trial should not affect whether a participant decides to turn left or right in the next trial, it should instead depend on the message currently displayed).

Figure 34. Screenshots of the messages included on the variable message sign (VMS). a) Practice; b) Control; c) VMS short right; d) VMS short left; e) VMS long right; f) VMS long left.

Participants

The study was approved by the NRC Research Ethics Board (protocol # 2022-81). All participants provided written informed consent and filled out a COVID-19 self-assessment form prior to participating in the study.

A convenience sample of participants was recruited to complete the VR scenario. Participants were all at least 18 years of age and did not have any health conditions that could be exacerbated by VR (e.g., no eye disease, epilepsy, severe motion sickness). The research team conducted the pilot study with seven participants (six men, one woman) as the study was more exploratory.

Participants were recruited from the NRC and the general Ottawa/Gatineau community. Participants were recruited via email and word of mouth. Interested potential participants were provided with detailed information about the study and could schedule a session to take part in the study (if they met the inclusion criteria; see below).

Inclusion criteria:

- At least 18 years old
- Normal or corrected to normal vision

Exclusion criteria:

- History of cardiovascular or vestibular conditions or respiratory diseases
- History of epilepsy, severe motion sickness while traveling, eye disease, or recurrent migraines
- Symptoms of COVID-19 or having been exposed to COVID-19 within the last 14 days on the day of data collection
- Uncomfortable wearing Personal Protection Equipment for the duration of the study

VR Equipment

Participants were immersed in the driving scenario via a Vive Pro head-mounted display (screen: dual AMOLED 3.5" diagonal; resolution: 1440 x 1600 pixels per eye; refresh rate: 90 Hz; field of view: 110 degrees, https://www.vive.com/ca/product/vive-pro/). They wore headphones built into the head-mounted display, which played audio (e.g., vehicle engine, acceleration, braking). Two Vive 2.0 base stations (Lighthouses) tracked participants' head movements via the SteamVR plugin (version 1.23.7, https://www.steamvr.com/en/). Each base station was installed on a Manfrotto clamp arm. The driving scenario was run on an HP Z8 G4 Workstation (Intel(R) Xeon(R) Gold 5118 CPU @ 2.30GHz 2.29 GHz (2 processors)) with an NVIDIA GeForce RTX 2080 graphics card. Participants navigated in the virtual environment via a Thrustmaster 300RS steering wheel and acceleration and brake floor pedals (https://www.thrustmaster.com/en-gb/products/t300rs/). Participants filled out online questionnaires on a separate computer. See Figure 35 for a photo of the experimental setup.

Figure 31. Illustration of a participant immersed in the driving simulation.

VR Driving Scenarios

Participants completed a total of six trials: (1) Practice, (2) Control, (3) VMS right short message, (4) VMS left short message, (5) VMS right long message, and (6) VMS left long message. The order of the control and experimental trials was randomly assigned. Additional details about the scenarios are provided below.

The VMS was approximately 1.90 m (width) by 1.90 m (height) in the virtual environment. In all trials, the text of the VMS was displayed in amber on a black background, in capital letters using the Unity TMP Font Asset "Datcub-eZO2g SDF" (size 2.81) and in English only.

In all trials, participants were the driver (no passenger) and viewed the scenario from a first-person perspective. Participants were told that the speed limit is 40 km/h as they were driving in a residential area. This instruction also intended to avoid any confusion about driving speed. Aside from the plume of smoke seen in the distance, the scenario did not contain any other visual effects (e.g., no ember showers) or other vehicles (see Figure 32b).

Practice Trial
The practice trial took place on the same road as the experimental trials; however, the VMS displayed the message "REPORT WILDFIRES!" instead of a specific action to follow. Participants began the trial in the driveway of one of the houses in the neighbourhood (see Figure 36 for a screenshot). Their task was to drive on a straight two-lane road (i.e., one single-vehicle width lane in each direction) until they reached the VMS (approximately 1 km away). The VMS was placed at a three-way junction (see Figure 36 for a screenshot) and participants needed to decide whether to turn left or right (no correct direction). Once participants turned left or right, the practice trial ended.

Control and Experimental Trials
Participants' task in the control and experimental trials was identical to the practice trial. Participants began the trials in the same location and drove on the same two-lane road as the practice trial. Participants encountered the same three-way junction as the practice trial, except that during the control trial, participants were exposed to a blank VMS (no correct direction) and during the experimental trials, the VMS displayed a message instructing participants to turn in a specific direction (i.e., left or right). Once they turned left or right, the trial ended and the next trial began. Once participants completed all the trials, they were asked to fill out the post-scenario online questionnaires.

Measures
All the questionnaires were entered into LimeSurvey, an online survey platform (https://www.limesurvey.org/). Participants filled out questionnaires prior to and following the VR driving scenario.

Demographic Questionnaire. Prior to the experiment, participants filled out the demographic questionnaire, which included questions about their age, gender, driver's license, driving experience and frequency, VR and gaming experience, and previous experience with evacuating from a wildfire.

Driving Scenario. This questionnaire inquired about the urgency and realism of the scenario (e.g., "How urgent did you perceive the evacuation", see Table 17 for additional questions). It is rated on a 7-point scale (from -3 = "Not urgent at all/No risk at all/Very unrealistic" to + 3 = "Very urgent/Very high risk/Very realistic"). The questionnaire was administered following the VR driving scenario. A higher (positive) score represents higher urgency, risk, realism, etc.

a)

b)

c)

Figure 32. Screenshots of routes that participants followed during all trials. a) bird's eye view of start position; b) bird's eye view of VMS at three-way junction; c) bird's eye view of full route that participants drove.

Variable Message Signs (VMS). This questionnaire asked participants to select the VMS that was, e.g., the most noticeable, easiest to distinguish, easiest to understand, etc. (see Table 17 for additional questions). The questionnaire was administered after the VR driving scenario.

Trajectory Data. During the VR driving scenario, the experimenter manually recorded (i.e., via pen and paper) participants' driving trajectory to assess whether they followed the directions on the VMS.

Usability. This questionnaire inquired about user experience in the virtual environment (e.g., ease of use of the VR driving simulator, see Table 17 for additional questions). It is rated on a 5-point scale (from 1 = "Strongly disagree to 5 = "Strongly agree"). A higher score represents higher usability. The questionnaire was administered following the VR driving scenario.

Presence. This one item inquired about participants' feeling of "being there" in the virtual environment on a 10-point scale (from 0 to 10, see Table 17 for the item). A higher score represents higher presence in the virtual environment. The item was administered after the VR driving scenario.

Virtual Reality Sickness Questionnaire (VRSQ). The Virtual Reality Sickness Questionnaire is a short version of the Simulator Sickness Questionnaire (SSQ), used to assess cybersickness (unwanted VR-related side effects such as nausea or dizziness). This questionnaire asked participants to rate how much the following symptoms are affecting them on a scale of 0 (None) to 3 (Severe): General discomfort, Fatigue, Eyestrain, Difficulty Focusing, Headache, Fullness of head, Blurred vision, Dizzy (eyes closed), Vertigo. A higher score represents higher cybersickness (see Kim et al., 2018 for scoring procedure). The Virtual Reality Sickness Questionnaire was administered after the VR driving scenario.

Qualitative Feedback. Participants were invited to provide open-ended feedback after the VR driving scenario. Questions inquired about participants' overall satisfaction with their VR experience, whether there were any specific components about the driving simulation that they liked or did not like, whether they thought any improvements could be made to the driving simulation, etc. (see Table 17 for additional questions).

Table 17. Questions included in each measure.

Measure	**Questions**
Driving Scenario	1- How urgent did you perceive the evacuation? 2- How high risk did you perceive the wildfire to be? 3- How realistic was the risk of harm from the wildfire? 4- How convincing was the visualization of the wildfire scenario? 5- How realistic was the driver cabin of the car? 6- How realistic was the landscape (including roads and buildings) in the scenario? 7- How realistic was the virtual environment?
Variable Message Signs (VMS)	1- Which of the variable message signs is the most noticeable? 2- In which of the variable message signs are details the easiest to distinguish? 3- Which of the variable message signs is the easiest to understand? 4- Which of the variable message signs best conveys the message that you should follow the detour? 5- Which of the variable message signs overall offers the best support for your evacuation?
Usability	1- I thought the VR driving simulator was easy to use. 2- I felt comfortable using the VR driving simulator. 3- I could effectively complete the tasks and scenarios using the VR driving simulator. 4- The VR driving simulator has all the functions and capabilities I expect it to have. 5- I liked the interface of the VR driving simulator.
Presence	On a scale from zero (0) to ten (10), to which extent do you feel present in the virtual environment, as if you were really there?
Cybersickness	1- General discomfort 2- Fatigue 3- Eyestrain 4- Difficulty focusing 5- Headache 6- Fullness of head 7- Blurred vision 8- Dizzy (eyes closed) 9- Vertigo
Qualitative Feedback	1- How satisfied were you overall with your VR experience? Why? 2- Are there any specific components about the VR driving simulation that you liked and/or did not like? Please explain why you liked or did not like them. 3- Which variable message sign did you prefer? Why? 4- What improvements do you think could be made to the VR driving simulation? 5- What other comments do you have about your experience?

Procedure
Prior to the experiment, participants read and signed the informed consent form. They also filled out a COVID-19 self-assessment form to confirm that they did not have any COVID symptoms. The experimenter then briefly verbally explained the steps of the study. Participants then filled out the online demographic questionnaire. Once participants were finished filling out the questionnaire, the experimenter asked whether they had any questions and explained how to use the VR equipment. Once participants confirmed being comfortable and ready to begin the experiment, the experimenter explained the VR driving task to complete. Participants then completed the practice trial (approximately 2 minutes) followed by the experimental trials (approximately 2 minutes each). While participants completed the trials, the experimenter observed them via computer monitor (to make sure that there were no technical issues and to take notes if needed (e.g., unexpected actions, technical issues, cybersickness) to make improvements to the driving scenario. The experimenter also manually recorded participants' trajectory.

Following the experiment, participants filled out the questionnaires about their experience in the scenario and provided some open-ended feedback. The experimenter then verbally debriefed participants. First, the experimenter explained the study objectives in more detail, then made sure that participants were not experiencing any lingering cybersickness and asked whether participants had any questions. Finally, the experimenter thanked participants for taking part in the study.

See Figure 37 for a flowchart of the data collection process.

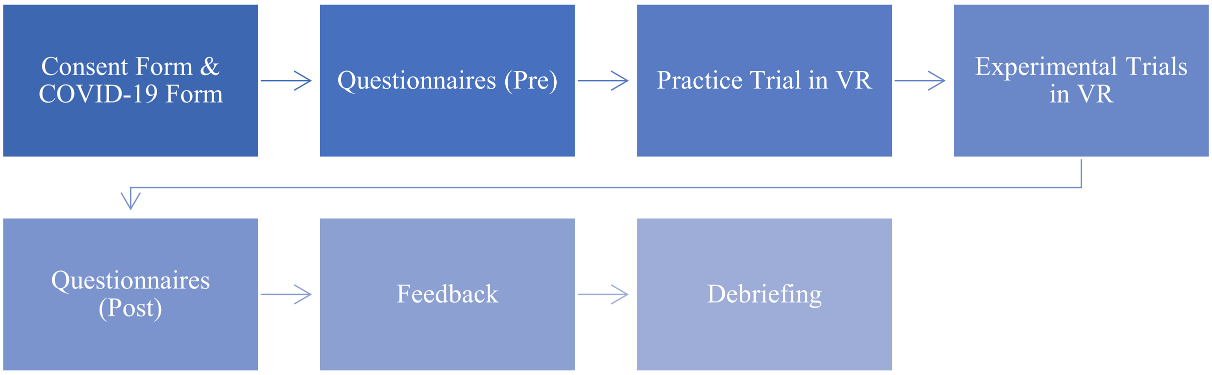


Figure 33. Data collection process for the pilot study.

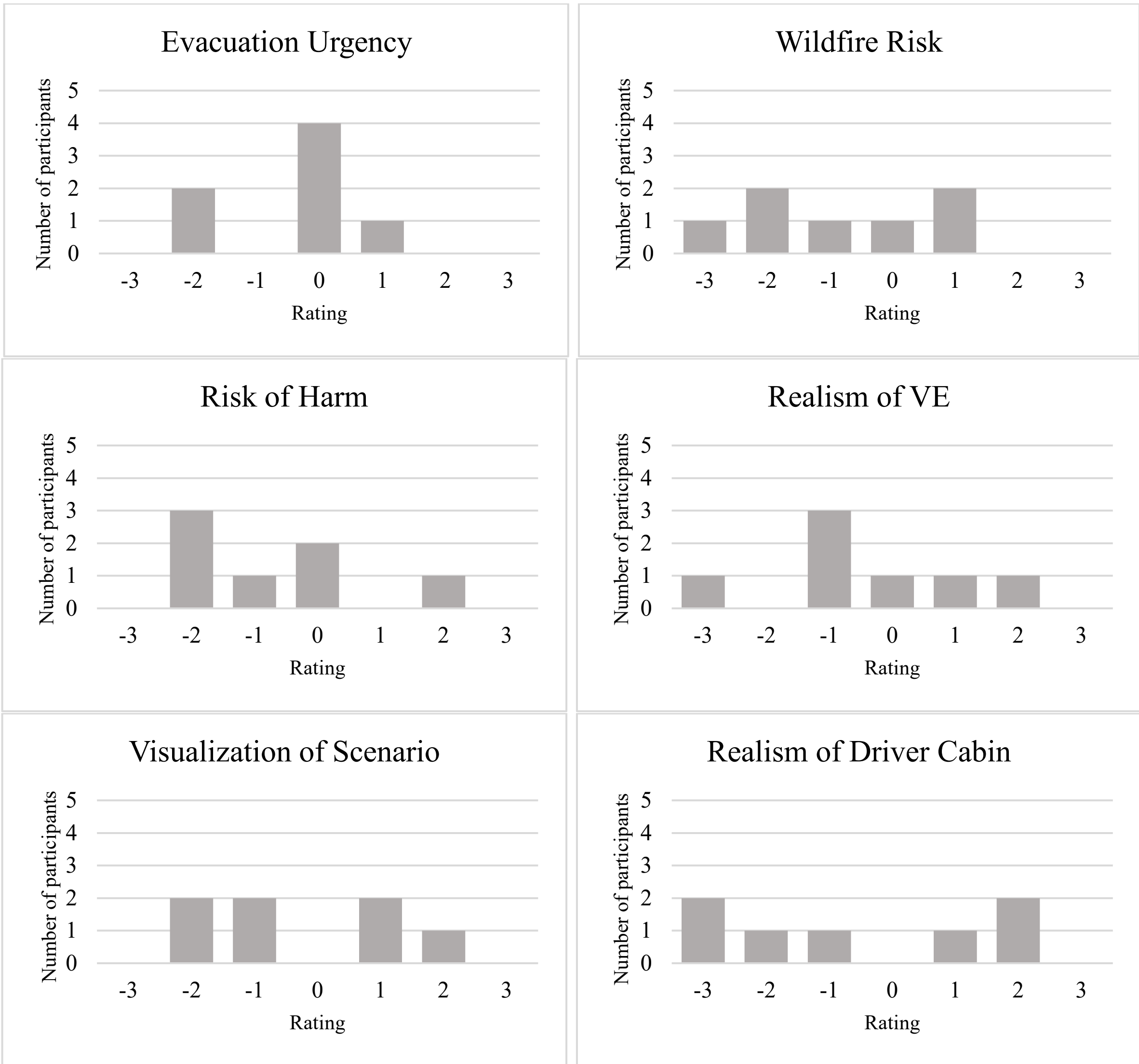
Results
Below are the results of descriptive analyses with the pre-scenario and post-scenario data of the seven participants.

Pre-Scenario
Participants' age ranged between 29 and 43 years old (M = 35.71, SD = 4.96). None of the participants had any health conditions or had previously experienced evacuating from a wildfire. All participants had a valid driver's license or were in the process of obtaining one and reported driving daily. Five participants have had their driver's license for over ten years and two have had it for six to ten years. Participants drive on average 17,000 km per year (SD = 10,969.66). They also reported having little previous experience using VR and having more experience playing video games on a PC or a console (e.g., PlayStation, Xbox, Wii). Specifically, all participants have tried VR once or a few times. Three participants have played video games on a PC or a console once or a few times, two play a few times per month, and

two play weekly. In addition, cybersickness symptoms prior to the immersion in VR were relatively low with mean of 4.64 (*SD* = 5.83) out of a possible 100.

Post-Scenario

Driving Scenario. Most participants perceived the urgency of the evacuation and the risk of the wildfire as low. Many also rated the risk of harm from the wildfire, the realism of the visualization of the wildfire scenario, and the realism of the driver cabin as relatively low. However, they rated the realism of the landscape slightly higher. Note that the highest possible score is +3 and the lowest possible score is -3 (see Figure 38 for results). Many participants mentioned that they did not feel threatened by the smoke as it was so far away.



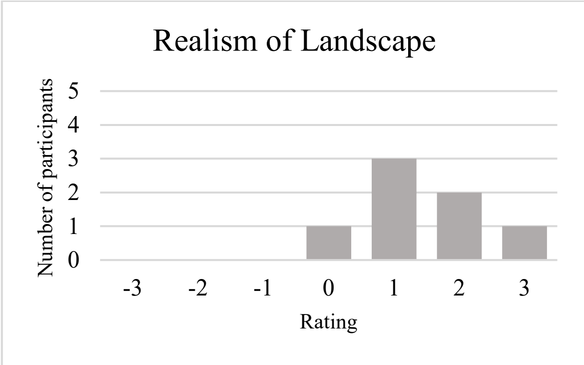


Figure 34. Participants' ratings of the VR driving scenario. Note: VE = virtual environment.

VMS. Most participants followed the instructions on the VMS. The results suggest that the shorter messages were more noticeable (for 4 out of 5 participants), easiest to understand (for 4 out of 6 participants), their details easiest to distinguish (for 4 out of 5 participants), best convey the message to follow detour (for 4 out of 6 participants), and overall offer the best support for evacuation (for 4 out of 6 participants). However, caution should be used when interpreting the results as two participants mentioned having trouble reading the text on the VMS from a distance and as such, being unable to answer these items. The research team will explore using a different font package and increasing the size of the VMS and the font for future studies.

Usability. The results suggest that the driving simulator's usability could be improved (the highest possible score for each question is 5, see Figure 39). In general, participants reported that the driving simulator had all the functions and capabilities that they expected it to have and that they were comfortable using the simulator. Participants also indicated that they were able to complete the driving task. However, the results show that the interface of the driving simulator could be improved and that it was somewhat difficult to use. For example, many participants mentioned that they had to press harder on the acceleration pedal in the virtual vehicle than they would in a physical vehicle, which decreased the realism of the VR scenario.

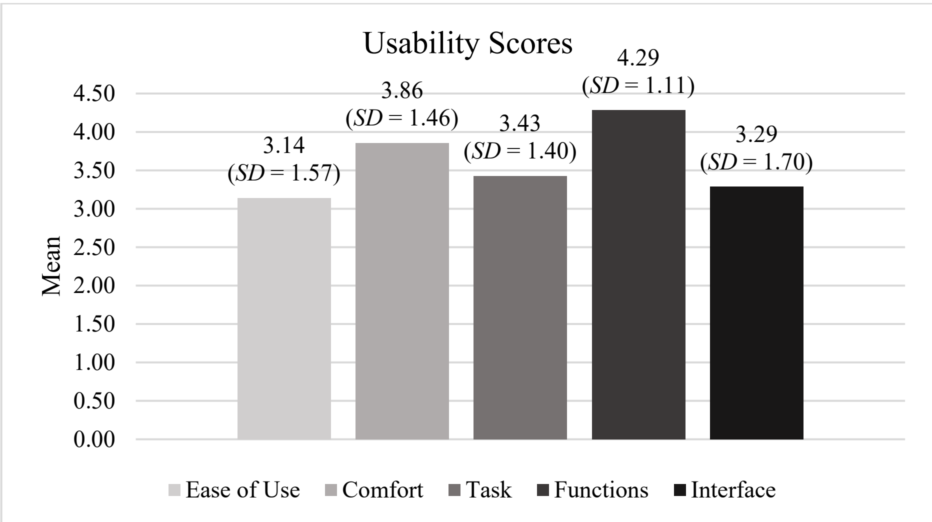


Figure 35. Participants' ratings of the usability of the VR driving scenario. Standard deviations in brackets.

Presence. Participants reported low presence, with a mean of 3.86 (*SD* = 2.67) out of a possible score of 10. This result may be due to the driving not feeling as realistic as participants expected.

Cybersickness. Following the immersion in the VR driving scenario, participants experienced higher cybersickness. However, the scores remained relatively low, with a mean of 9.64 (SD = 9.60) out of a possible total score of 100. As the sample was small, a Wilcoxon Rank-Sum Test was used (RStudio, version 2022.02.3, Build 492). The results (see Figure 40) showed that the difference between pre-scenario and post-scenario cybersickness scores was not significant ($W = 3.00, p > .05$).

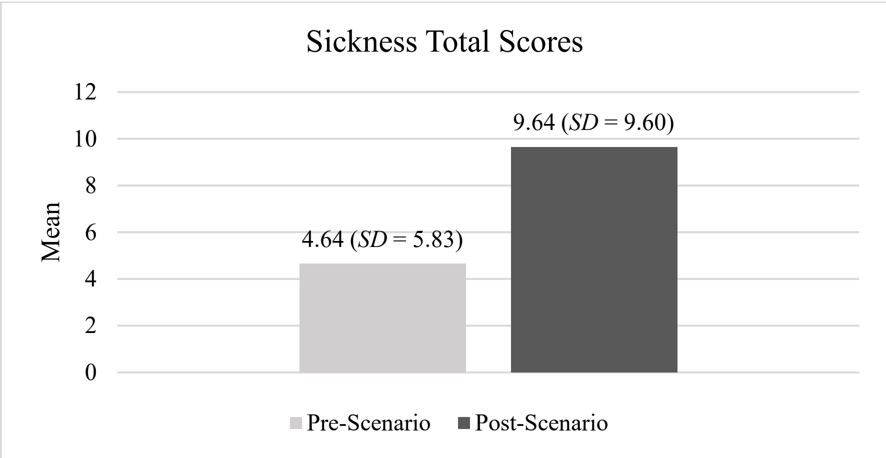


Figure 6. Participants' ratings of cybersickness pre- and post-scenario. Standard deviations in brackets.

Qualitative Feedback. In the feedback survey, participants suggested to make improvements to the VR driving simulation. For example, many participants reported that the steering and the acceleration felt unrealistic compared to driving in the real-world and suggested to improve the sensitivity of the steering wheel and acceleration pedal. One participant mentioned that this difference in sensitivity negatively affected his feeling of being in the virtual environment. A few participants also suggested improving the vehicle audio as they found the sound of the engine unrealistic. One participant also mentioned that the rendering of the virtual environment felt slow, which might be due to the size of the virtual environment's terrain. One participant suggested to add a stop sign or another road sign before the VMS to capture their attention and prompt them to attend to the message on the VMS. Although many suggestions were made to improve the driving simulation, many participants reported in the online survey or verbally that the virtual environment looked visually realistic and convincing.

Discussion

The main objective of the pilot study was to assess the usability of the VR driving simulation and whether any changes need to be made to the study protocol and/or the simulation prior to recruiting a larger sample.

The results of the post-scenario questionnaires showed that most participants rated the urgency of the evacuation and the risk of the wildfire as low. They also perceived the realism of the risk of harm from the wildfire and the visualization of the wildfire scenario as relatively low. This might be due to the fact that the VR driving scenario did not contain any environmental conditions related to wildfires (aside from the plume of smoke seen in the distance). In the next study, the research team will use the "wildfire" scenario containing visual effects such as ember showers and fog/haze. These environmental conditions should increase participants' perception of the urgency of the evacuation, the risk of the wildfire, and the realism of the wildfire scenario.

In addition, traffic will be included in a future version of the driving scenario, which should also increase the realism of the scenario.

A few participants reported that the VMS was difficult to read from a distance. The research team will investigate using a different font package and enlarging the VMS to improve legibility. In addition, they will explore the possibility of including a road sign or another prompt to ensure that participants attend to the message on the sign. For example, in one study (Ronchi, Nilsson, Modig, et al., 2016), the authors used flashing lights on the VMS to attract participants' attention.

Most participants experienced some cybersickness while driving in the scenario, which could be related to perceiving movement visually (i.e., scene is moving as one drives) but not feeling any corresponding vestibular movement (i.e., the vehicle is not moving the physical environment). The cybersickness could also possibly be due to the update rate of the virtual environment (i.e., lags between moving in the virtual environment and the updating of the scene). The performance of the simulator will continue to be optimized in future versions of the scenario.

Generally, the usability results suggest that participants were able to complete the driving task and that the driving simulator had the features that they expected a vehicle to have. However, the interface could be improved. Based on the participants' questionnaire responses and feedback, the research team will make improvements to the driving simulation, particularly with regards to the sensitivity of the steering and acceleration. The research team will also make changes to the vehicle audio (e.g., refining the sound of the engine). These improvements should increase participants' feeling of presence in the virtual environment as the driving experience should be more aligned with their expectations.

Lessons Learned & Future Directions

This pilot study was the first data collection using the VR driving simulator. Although it was a simplified scenario that did not include environmental conditions associated with wildfires, it was an important first step to assess the usability of the simulator and collect initial feedback from participants. This feedback will help the research team optimize the driving simulator and design future studies with a larger number of participants.

Additions and refinements are currently being made to the scenarios. For example, a night time version of the scenarios is under development. In addition, the traffic system is being refined (e.g., ability to define the route of an individual AI vehicle relative to the user's position, fine-tuning the AI vehicles' behaviour). Additional functional elements, such as a radio, a navigation display application and/or other method of communication to keep evacuees informed (e.g., of announcements, warnings, detours/road closures) will also be implemented. Fire, smoke, haze/fog, and embers are also being added to the scenario.

In terms of future studies, the research team will conduct further piloting of the refinements currently being made to the scenarios. In addition, the effect of environmental manipulations and traffic on driving behaviour and decision-making will be examined. For example, it would be of interest to explore how traffic and reduced visibility impact individual driving behaviour during a wildfire evacuation. Studying variables such as headway and congestion would also be of interest.

7. The enhancements and integration of the k-PERIL model

Trigger buffers were first introduced in WUINITY through the PERIL algorithm (Mitchell et al., 2023), where an evacuation trigger perimeter could be calculated for a specific rural community via wildfire and evacuation simulation. The algorithm was based on the work of Cova et al from (Dennison et al., 2007; Larsen et al., 2011; Li et al., 2017). PERIL was later rewritten with the express purpose of being natively included in WUINITY, and was renamed to k-PERIL. This is the version most recently introduced in WUINITY 2 (Ronchi et al., 2021). Since WUINITY 2, k-PERIL has progressed to a completely stochastic trigger model generation algorithm, combining the work of (Ramirez et al., 2019). The newest version is in the process of being integrated to WUINITY, and initial work has been completed.

An initial indication of the stochastic capabilities of k-PERIL was displayed when presenting k-PERIL's ability to compound multiple boundaries, created by different wildfire-evacuation simulation sets, into a single boundary. This capability was since expanded, with k-PERIL now being run stochastically on a probabilistic simulation basis (see Figure 41). The user can now run a large number of wildfire-evacuation simulation pairs, varying the input values of weather, ignition location, and evacuation behaviour. The resulting trigger boundary of each such simulation is then compounded to an overall probabilistic trigger boundary. With this new method, the result is not a singular trigger line around an area, but a probabilistic cloud represented by iso-probabilistic lines around an area (see Figure 42).

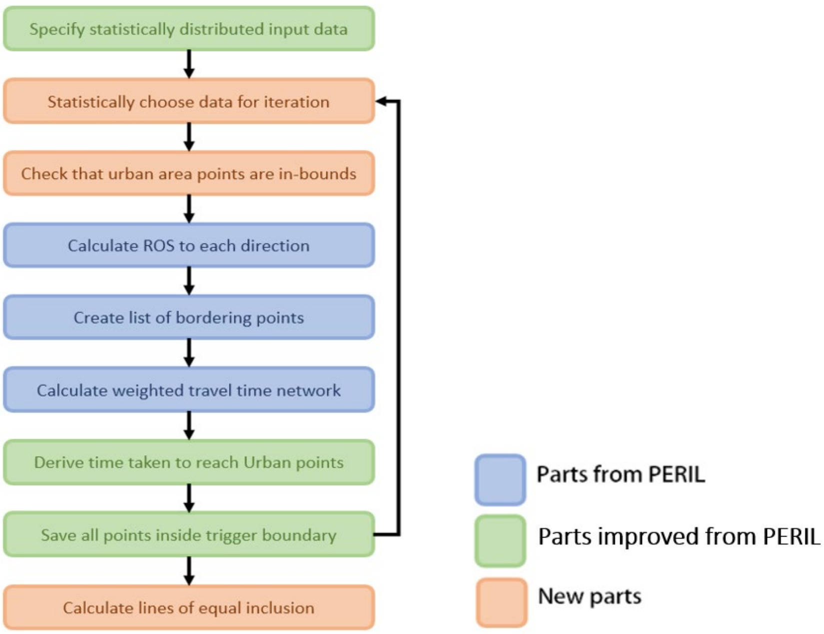


Figure 41. The core algorithm of k-PERIL, with colour coded changes from PERIL (Mitchell et al., 2023).

The change to stochastic trigger boundaries allows for analyses to be conducted for specific areas and periods rather than specific wildfires. A populated area can be selected, input parameters can be provided as probabilistic variables, and k-PERIL will run a large number of simulations for the entire area. The resulting stochastic trigger boundary will be valid for any wildfire that may threaten the area and thus can be used in emergency planning.

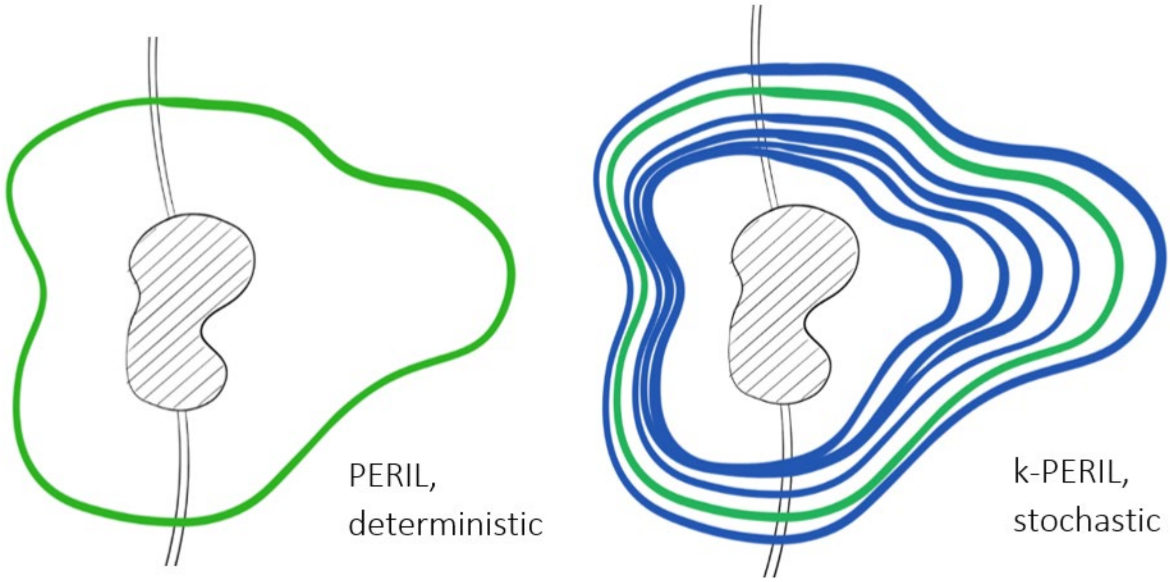


Figure 42. Example of a singular trigger boundary (green) surrounding an urban area (hatched), connected to two roads on the north and south (left). The same area with stochastic trigger buffers (right). The green boundary here represents the line of 5% inclusion. Areas with dense lines on the west indicate low variability, while areas with sparse lines on the east indicate high variability.

Stochastic trigger boundaries also display information regarding the variability of the wildfire-evacuation sets, pointing out areas of increased danger. Areas where the iso-probabilistic lines are spaced further apart indicate that either the evacuation or the wildfire are very sensitive to the ambient conditions. When wildfires approach the area from directions with increased spacing, their effect to the area and the available evacuation time are greatly variable and increase the risk posed to the community.

The ability of stochastic trigger boundaries to provide risk assessment information for an entire area and not only for specific wildfires means that the resulting trigger boundaries can be used as a criterion for future works pertaining to evacuation and fire safety. Actions that have an effect on the progress of the evacuation or the spread of the wildfire can be tested on the resulting stochastic trigger boundary they generate. Ideally such actions should aim to create compact boundaries, with very little spacing between the iso-probabilistic lines, and should make the entire boundary move closer to the target community, as that implies the fire is slower moving towards the area. A trigger boundary closer to the community would also help with evacuation as more people would be incentivised to evacuate before an official order is given, encouraged by the perceived position of the fire and the smoke plume.

8. The WUI-NITY Graphic User Interface enhancements

WUI-NITY has been developed as a platform for the simulation of wildland-urban interface fire evacuation through collective efforts (Ronchi et al., 2020, 2021). At the first stage of developing the platform, three main goals were achieved: identifying the required data sets, selecting the component models based on performance criteria, and implementing fire, pedestrian, and traffic modelling layers into a single modelling environment. As an initial stage of development, the implementation of WUINITY is mainly for the purpose of demonstrating the proof of concept of all functionalities. As a result, the first release of WUI-NITY is primarily a research tool.

To enhance the credibility of WUI-NITY and develop it into a more practical engineering tool, two steps have been taken and are documented in this section. First, the data preparation process was reviewed to clarify the data required to construct a simulation model and the process by which this is achieved. A generalised workflow was built to guide the user to formulate the inputs and configure a simulation. Based on the workflow, the usability of the platform was enhanced through the development a new workflow-based graphical user interface (GUI).

8.1 Data preparation and user input

The user is required to provide a range of inputs in order to configure the model. Not all of these are required at all times (e.g., the fire might not always be modelled). However, a clear understanding of each data input and the user actions attached to them is key to inform our assessment of the overall workflow and then the development of the GUI. This section addresses inputs within five different areas: map preparation, population definition, fire and smoke simulation, traffic network and routing, and evacuation settings.

8.1.1 Map preparation

WUI-NITY uses a 3rd party map application called Mapbox to render the map as the foundation layer to show the location of various other components, such as the evacuation traffic, evacuation goals etc. For the Mapbox APIs to access the service, an API access token is required if it is not already built within the WUI-NITY release package. The access token can be created at https://account.mapbox.com/ with a registered account.

As the first step to building a wildfire evacuation simulation project, the location and size of the region (usually a rectangle) are to be specified by the user. These include the latitude and longitude GPS coordinates of the bottom left corner in decimal degrees, and the length of the rectangular region in X and Y directions. Finally, the map zoom level with a default value of 13x is used to render the map in WUI-NITY.

The user input of the location and size of the region is also used in other modules of WUI-NITY to configure the wildfire evacuation simulation project (for instance, in defining the population distribution and routing). The data input relating to the map preparation is shown in Table 18.

Table 18. Data preparation and user input for map.

Input name	Format	Default value	Explanation/Source
Map LL latitude	Decimal degree	-	The latitude of the lower left corner of the map.
Map LL longitude	Decimal degree	-	The longitude of the lower left corner of the map.
Map size x [m]	Decimal	10,000 m	The width of the map (in horizontal X direction) in meter covering the area of interest.
Map size y [m]	Decimal	10,000 m	The height of the map (in vertical direction Y direction) in meter covering the area of interest.
Map zoom level	Decimal	13	The best-fit scale of satellite image to show the map within the GUI window.
Mapbox API access token	String	-	Create at https://account.mapbox.com if it is not already built within WUI-NITY.

8.1.2 Population definition

WUI-NITY uses the Gridded Population of the World (GPW) collection as the basis to create and configure the population in evacuation simulation. The GPW data sets model the distribution of the global human population on a continuous raster surface with an output resolution of about 1 km. The data sets can be downloaded from the following link: https://sedac.ciesin.columbia.edu/data/collection/gpw-v4/sets/browse

The GPW data sets are processed in three steps before the population data is loaded into the evacuation simulation. First, a subset of raw GPW data covering the area of interest (i.e. the region specified in the steps in Section 8.1.1) is extracted from the global GPW data sets. Second, the raw GPW data is interpolated according to the chosen evacuation cell size (see Section 8.1.5). And finally, the population is re-distributed according to the configuration of the local road network, assuming people are living within a certain distance to the roads. The data input relating to the population definition is shown in Table 19.

Table 19. Data preparation and user input for map.

Input name	Format	Default value	Explanation/Source
Map LL latitude	Decimal degree	-	The latitude of the lower left corner of the map.
Map LL longitude	Decimal degree	-	The longitude of the lower left corner of the map.
Map size x [m]	Decimal	10,000 m	The width of the map (in horizontal X direction) in meter covering the area of interest.
Map size y [m]	Decimal	10,000 m	The height of the map (in vertical direction Y direction) in meter covering the area of interest.
Map zoom level	Decimal	13	The scale of satellite image to show the map within the GUI.
Mapbox API access token	String	-	Create at https://account.mapbox.com if it is not already built within WUI-NITY.

8.1.3 Fire and smoke simulation

Seven different files are required to provide data input regarding the simulation of the fire and smoke. These include the following data formats discussed below: .lcp, ,fuel, .fmc, .wtr, .wnd, .ign, and .gfi. In addition, several other settings are available relating to the spread mode, the wind multiplier, the random generation of the initial fire ignition, and the identification of the FARSITE data file. The fire definition that references these files is shown in Table 20.

Table 20. Input files for fire and smoke simulation.

File type	Postfix	File preparation and specification
lcpFile	.lcp	A combination of elevation, slope, aspect, canopy cover and fuel raster layers prepared by the user following the guidance provided in this section. The files are readily available for locations in the US.
fuelModelsFile	.fuel	Typical fuel types found in a specific geographic location and their combustion properties. A default LANDFIRE's (LF) 13 Anderson Fire Behavior Fuel Model (FBFM13) is available for use.
initialFuelMoistureFile	.fmc	User definable level of moisture of each type of fuel.
weatherFile	.wtr	User definable weather conditions (precipitation, temperature, and humidity).
windFile	.wnd	User definable wind speed and direction as a function of time.
ignitionPointsFile	.ign	User definable location and time of ignition point.
graphicalFireInputFile	.gfi	User definable WUI area, initial ignition, random ignition, and trigger buffer mapped on the fire mesh.

The creation and preparation of the seven file types listed above are now presented.

LCP file (.lcp):
The fire simulation model requires a landscape file (.lcp) to simulate the spread of fire and smoke. A landscape file is a combination of elevation, slope, aspect, canopy cover and fuel raster layers. If the target location is within the United States, users can use the readily available landscape files at LANDFIRE database[16]. If the target location is outside the United States, the raster layers need to be individually located, downloaded, modified and combined using a GIS program. The raster layers can be found using the below sources (not exhaustive). Slope and aspect layers can be calculated from the elevation layers using GIS.

- **Elevation:** Earth Explorer[17], Earth Engine[18], local survey authority
- **Canopy Cover:** European Forest Fire Information System (EFFIS)[19], local survey authority
- **Fuel Model:** European Forest Fire Information System (EFFIS), local survey authority

The fuel model may be difficult to obtain in many countries as it requires extensive manual surveying.

All raster layers then need to be set to the same dimensions use and the EPSG:3857 - WGS 84. Mercator map projection. This can be done using QGIS (free) or ArcGIS (commercial). QGIS was used in this study, and required the following steps:

- Make sure any base map used is set to EPSG:3857 - WGS 84.
- Create and save slope and aspect file from the elevation file using the tools in Raster -> Analysis.
- Draw a shapefile around your target area.
- Use the Geoprocessing Tools -> 'Clip' functionality to identify the elevation file to the shapefile extents to create a 'Clipped Extent' layer.
- Set all raster layers to the same properties:
    - Right click each layer in the QGIS browser.

[16] https://landfire.gov/getdata.php
[17] https://earthexplorer.usgs.gov
[18] https://earthengine.google.com
[19] https://effis.jrc.ec.europa.eu/applications/data-and-services

- Use 'Save as' to change projection, change resolution (any resolution is fine, but it is important that all layers have the same resolution) and clip it to the 'clipped extent' layer.

The standardised raster layers now need to be combined using one of the two specialist programs:

- FlamMap (QGIS)
  - Click on: Landscape,
  - Click on: Create Landscape file,
  - Upload the raster layers under 'required themes',
  - Save as an .lcp in the WUINITY project folder.
- ArcFuels (ArcGIS)
  - Click on: Build LCP -> Build LCP using Raster Data,
  - Add the needed raster images under 'Raster Data',
  - Click on: 'output',
  - Use coordinates or another layer to define the LCP image boundaries,
  - Click on: Build LCP,
  - Save it in the WUINITY project folder.

Fuel models file (.fuel):
The fuel models file stores the typical fuel types and their combustion properties found in a specific geographic location. The user can provide their own data should they have precise data that can describe the type of fuels identified in the area of interest or use the default Anderson Fire Behaviour Fuel Model (FBFM13)[20] (Anderson, 1981). The file has 17 fields in each line which define one type of fuel, following the order given in the first line. See an example in Table 21.

Table 21. An example of a .fuel file with three default types of fuel.

fuelModelNumber, code, name, fuelBedDepth, moistureOfExtinctionDead, heatOfCombustionDead, heatOfCombustionLive, fuelLoadOneHour, fuelLoadTenHour, fuelLoadHundredHour, fuelLoadliveHerbaceous, fuelLoadliveWoody, savrOneHour, savrLiveHerbaceous, savrLiveWoody, isDynamic, isReserved 1, "FM1", "Short grass [1]", 1.0, 0.12, 8000, 8000, 0.034, 0, 0, 0, 0, 3500, 1500, 1500, false, true 2, "FM2", "Timber grass and understory [2]", 1.0, 0.15, 8000, 8000, 0.092, 0.046, 0.023, 0.023, 0, 3000, 1500, 1500, false, true 3, "FM3", "Tall grass [3]", 2.5, 0.25, 8000, 8000, 0.138, 0, 0, 0, 0, 1500, 1500, 1500, false, true

There is an associated initial fuel moisture file (.fmc) which defines the level of moisture of each fuel type.

Weather file (.wtr):
The weather file provides an input of weather conditions (precipitation, temperature, and humidity) to the simulation model of fire and smoke spread. The file has ten fields in each line which define the weather conditions on a given day, following the order given in the first line. An example is given in Table 22.

20 https://www.landfire.gov/fbfm13.phpLANDFIRE Program: Data Products - Fuel - 13 Anderson Fire Behavior Fuel Models

Table 22. An example of a .wtr file with the weather condition on two successive dates.

Month, Day, Precip, Hour1, Hour2, Temp1, Temp2, Humid1, Humid2, Elevation
7, 15, 0, 4, 16, 13, 33, 10, 10, 1803
7, 16, 25, 4, 16, 10, 30, 18, 15, 1803

Wind file (.wnd):
As part of weather conditions, wind is given in a separate wind file. The file has two acceptable formats. The first one contains four fields in each line, which define the speed (km/h) and direction (in degrees) of a predominant wind condition from a given time measured in seconds, following the order given in the first line. In the second format, the wind condition is defined with time measured in month, day and hour, so that each line has six fields in the order of Month, Day, Hour, Speed, Direction, and CloudCover. An example is given in Table 23.

Table 23. An example of a .wnd file with three successive wind conditions in time.

Seconds, Speed, Direction, CloudCover
0, 10, 0, 0
3600, 2, 180, 0
7200, 10, 360, 0

Ignition points file (.ign):
The ignition points file stores the information about the location and time of ignition during a wildfire. It has three field in each line which define one ignition point, following the order given in the first line, i.e. Latitude, Longitude, IgnitionTime (in seconds). An example is given in Table 24.

Table 24. An example of a .ign file with two ignition point starting at different times.

Latitude, Longitude, IgnitionTime
39.479633, -105.037355, 0.0
39.450355, -105.040773, 3600.0

Graphical fire input file (.gfi):
WUINITY takes additional graphical input for fire and smoke simulation from the graphical fire input file. The graphical input initialises the fire mesh (defined according to the LCP file) with four types of information. They are the indices of WUI area, initial ignition, random ignition, and trigger buffer within the fire mesh. The ordered information in the graphical fire input file is stored in binary format corresponding to the size of the fire mesh. If a graphical fire input file is not available, WUINITY will initialise the fire mesh with null value.

8.1.4 Traffic network and routing
WUI-NITY utilises OpenStreetMap (OSM) data extracts to model evacuation via road network. The OSM data file (.osm.pbf) for a specific area of interest can be downloaded from:
https://download.geofabrik.de/index.html

The downloaded OSM data file is proceeded in two steps to build the traffic simulation model. First, a routing network database (.routerdb) for traffic pathfinding is calculated from the OSM data file. And based on the database, O/D matrices are calculated and stored as route collection file (.rc).

For the traffic simulation model, the user needs to specify the vehicle speed at maximum road capacity to avoid a complete stall of vehicle movement. The user can also select to enable the simulation of the impact of smoke on vehicle speed should the fire and smoke simulation being enabled.

8.1.5 Evacuation settings

The user can provide several inputs to affect the distribution of the population across space, the vehicle attribution and the speed and timing of evacuee movement (see Table 25).

Table 25. User definable evacuation settings.

Input name	Format	Default value	Explanation/Source
Evacuation cell size	Decimal	200 (m)	This defines the resolution of the population distribution within the region.
Max cars	Number	2	The maximum number of cars that can be assigned to a household.
Probability for max cars	Decimal	0.3	The likelihood that the maximum number of cars can be assigned to a household.
Min.-Max. persons per household	Number	1-5	The range of the number of persons assigned to a household.
Min.-Max. walking speed	Decimal	0.7-1.0 (m/s)	The range of walking speed of individual evacuees.
Evacuation order (time after fire ignition in seconds)	Decimal	-	The period of time between the fire ignition time and the moment when an evacuation order is given.

In addition, the user must provide three files to characterize the evacuation response specific resident groups. These are evacuation goal files, evacuation group files and response curves files. In this way, the resident population can be divided into different evacuation groups based on their location within the region. The user can then assign different evacuation goals and responses to the perception of fire and/or the evacuation order to the groups. The group definition is shown below – outlining the response profile and the movement goals for different groups.

Evacuation Group file

The Evacuation Group file defines an evacuation group with associated response curves and evacuation destinations (see Table 26). For each response curve and destination, a probability is assigned, indicating the likelihood of the agents in the group adopting the depicted response curves and evacuation destinations.

Table 26. The fields of evacuation group file and explanation.

Input name	Format	Explanation
Name	String	The identification name given to an evacuation group
Response curves	Array of string	The filename of response curves file(s)
Response curve probabilities	Array of decimals	The accumulative probabilities associated with the response curves.
Destinations	Array of string	The filename of evacuation goal file(s)
Destination probabilities	Array of decimals	The accumulative probabilities associated with the evacuation goals.
Colour	RGB values	The colour selected to draw the distribution of the evacuation group on map.

Response Curves file

The response curves file defines a cumulative probability from 0 to 1.0 as a function of time. It represents the likelihood of the agents deciding to evacuate. The file has two fields which are explained in Table 27.

Table 27. The fields of response curves file and explanation.

Input name	Format	Explanation
Time	Decimal	The time measured in seconds.
Cumulative probability	Decimal	A cumulative probability from 0 to 1.0

Evacuation Goals file

The evacuation goal file defines an evacuation goal and associated attributes. The file has nine fields which are explained in Table 28.

Table 28. The fields of evacuation goals file and explanation.

Input name	Format	Explanation
Name	String	The identification name given to an evacuation goal.
Latitude	Decimal degree	The latitude of the evacuation goal.
Longitude	Decimal degree	The longitude of the evacuation goal.
Goal type	options	Currently two types of goal are modelled in WUINITY: exit and refuge. The difference between them is that the latter has limited car and people capacity as specified in the fields below.
Max flow	Decimal	The max flow through the evacuation goal.
Car capacity	Number	The capacity of the goal in accommodating cars if it is a refuge area.
People capacity	Number	The capacity of the goal in accommodating people if it is a refuge area.
Initially blocked	Boolean	Whether the goad is available for use in the evacuation.
Colour	RGB values	The colour selected to draw the evacuation destination on map.

8.2 Guided workflow interface

The tasks required to put together a comprehensive model for simulating the combination of terrain definition, vegetation (as 'fuels'), atmospheric factors, fire growth, wildfire spread, road network, traffic model, and people movement require a fairly long and complex workflow. Data points need to be gathered from many different sources, and the eclectic and disparate nature of these data sources can become more complex because data are often in different formats for different countries. While the core UI for WUI-NITY does support the required functionality for data definitions for technically expert and highly experienced users, we also required the option of a User Interface layer which could help to guide new or infrequent users through the model definition and simulation processes; to make the software more "accessible". One option was to consider the type of ribbon-based interface[21] that Microsoft introduced with Windows 7 and the related release of MS Office. This design paradigm was adopted in order to reveal more functions to users and has been successful in that aim. However, while the ribbon interface can be useful, it was felt that it was not necessarily quite structured enough as a start-to-end interface which could reflect the nature of the data complexities required for our project.

One related, complex, workflow for technical software driving simulations is the work required for thermal-physics simulations of buildings to model energy performance, aimed at generating energy performance reports and certifications. One example of interfaces for this process, to guide users through the process of creating a detailed model, with thermal, geometric, and atmospheric properties is that which is termed the "workflow navigator" approach from Integrated Environmental Solutions. An example of this is the California Title 24 navigator interface[22]. These navigators can help in the process of guiding users through the "physics-model-creation-to-simulation-and-results" process, so it was decided to develop an interface which used the same design paradigms.

[21] https://learn.microsoft.com/en-us/windows/win32/uxguide/cmd-ribbons
[22] https://help.iesve.com/ve2021/4_2_title_24_navigator_interface.htm

The conceptual draft of the interface was in the following form, illustrated in Figure 43.

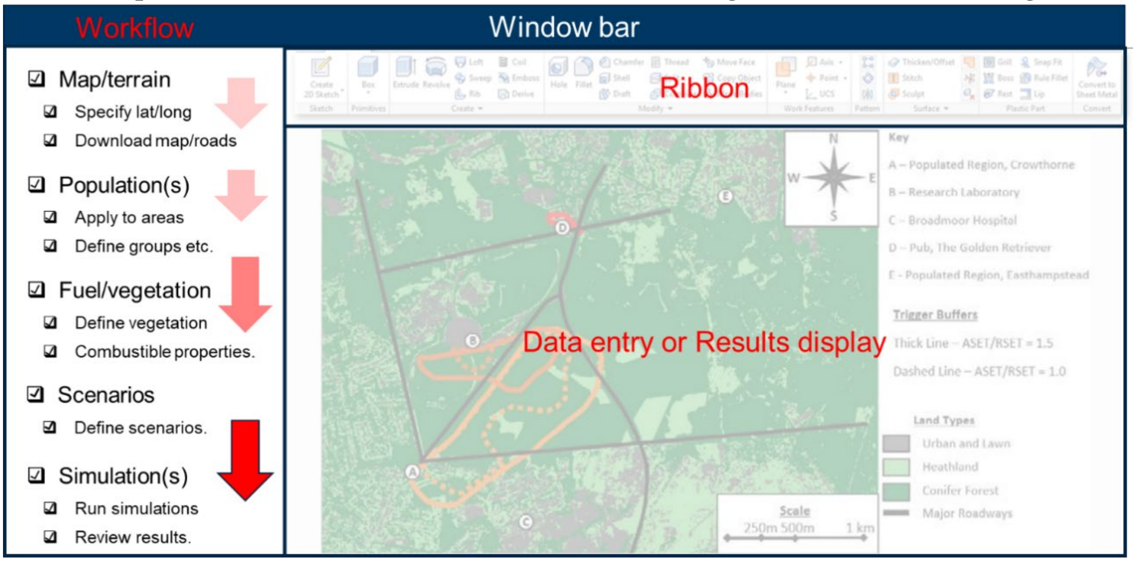


Figure 43. Initial conceptual sketch of the proposed UI layer.

The intention was to enable a collapsible hierarchy of interface, which reflected the start-to-end workflow. Each significant step or phase of model development is a collapsible branch, with each item in the "tree" not just tick-able (to track progress), but also fully functional. Each item can either serve directly as a data entry point or to launch a data definition or functional unit for simulation, such that the user may track their progress entirely from start to finish while executing the end-to-end workflow. Initially, it was considered adding a ribbon, but this seemed unnecessary with all functions enabled through the workflow navigation panel. However, to further guide the user, and after discussion within the team a "help" text panel was added which is updated whenever the user moves the mouse across a UI workflow element. The concept for this was thus adapted as illustrated in Figure 44; and also with some example indicative text, shown in the expanded UI concept example in Figure 45.

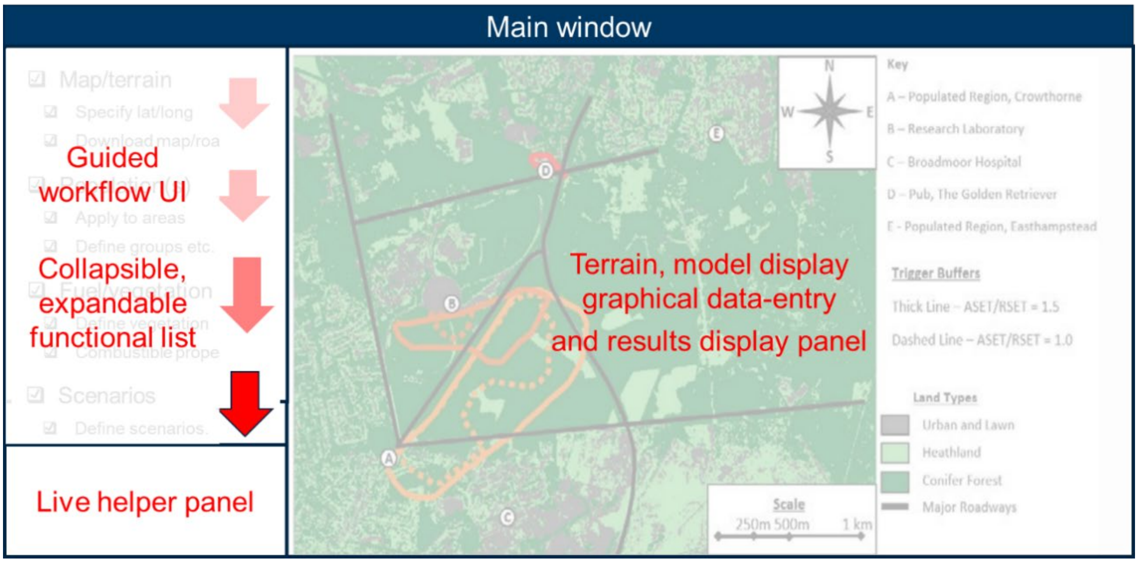


Figure 44. Secondary-phase UI conceptual sketch.

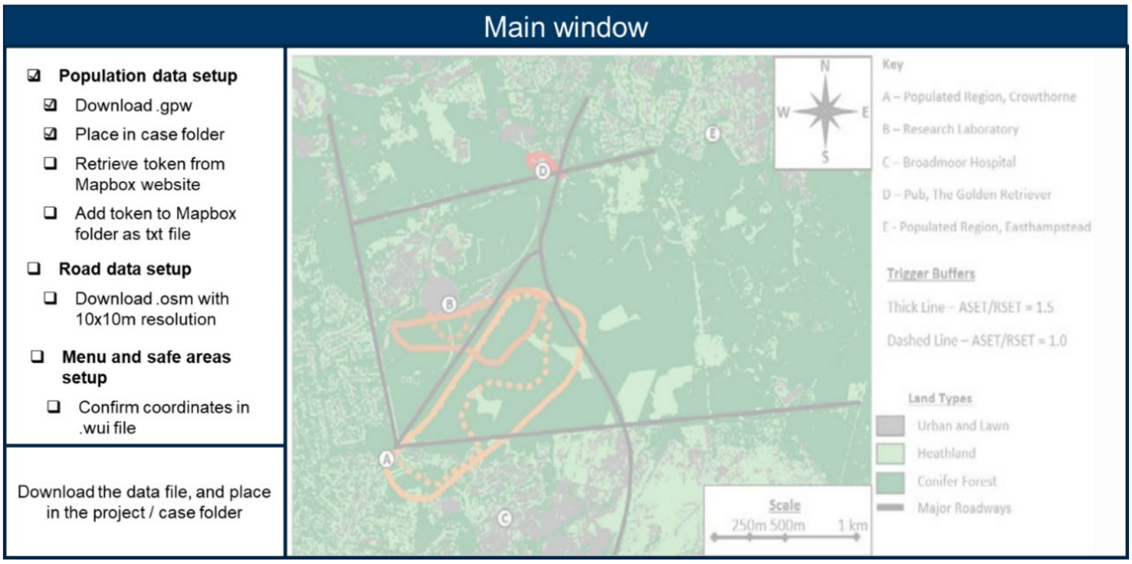


Figure 45. Expanded conceptual UI with indicative text (with reserved option of workflow being docked on the left or right hand side).

These form of top-to-bottom navigation panels with expandable branches are also seen in other technical packages such as Visual Studio (solution navigation) and are generally termed the "Vertical Navigation" design paradigm[23]. It seems to suit this complex workflow well, and was implemented (through learning and implementation processes) as described in the following sections.

8.2.1 Workflow process

Movement Strategies assigned a consultant engineer [24] to work through the technical tasks of data gathering, parameter-specification, and model setup to achieve a wildfire and evacuation model simulation for a sample site in the UK. The consultant engineer studied the existing user interface in WUI-NITY and also liaised with Lund University who was simultaneously working through tasks required to model wildfires in Sweden, as part of a masters research project (Jovlunden, 2023). As the engineer worked through the tasks, he documented the workflow steps as notes, which were then used to form the interface specification for the functional elements in the WUI-NITY workflow navigator panel. The workflow interface emerged from this functional discovery, noted in order of required processing, and converted to an XML file which the Unity "UI Toolkit" functionality uses to display visual elements to the user.

The emerging workflow was tested at several stages by asking clarifying questions to the software development team at Lund University. Initially, questions were centred on the landscape file (.lcp) creation process, which was the most time-consuming step of the workflow.

Subsequently, conversations around debugging the Marsden Moor casefile (see Section 8.4) were conducted with the Lund University staff allowing iterative updates to be made to the model and model configuration to ensure the traffic and fire simulations were running correctly – any procedural changes were reflected as a change to the overall workflow.

The master thesis work at Lund University (Jovlunden, 2023) was crucial to shape the workflow as it documented the steps used to interact with the model. This list formed an input to the UI

[23] https://uxdesign.cc/vertical-navigation-layout-usability-principles-10e55b596997
[24] Vai Saran

development and the creation of the Marsden Moor casefile. The aim of the thesis was to set up a WUINITY simulation in the Swedish landscape. Several issues were faced throughout the process, which are here outlined.

Fire simulation setup
WUINITY's fire simulation model requires a landscape (.lcp) file to run. It is a combination of several topographical layers and a fuel model. The target location for the research application fell outside of the United States. Therefore, a manual approach was required to create a landscape (.lcp) file which proved a time-consuming process.

1. Raster layers needed to be gathered from various sources. The locations that could be modelled were limited by the availability of topographical data.
2. Layers needed to be modified and cropped to the requirements of landscape file creation software ArcGIS or FlamMap.

Finally, manual changes to several .txt code files were required to fit other fire characteristics to the given location.

These issues were addressed over a protracted period of time – required the acquisition of knowledge in the following areas:

- GIS knowledge
- Knowledge of the appropriate fire model to be used in the target location
- Coding knowledge (modifying JSON files)
- General computer knowledge to troubleshoot errors

This knowledge proved useful in the creation of the Marsden Moor .lcp file.

Computer hardware
The work by (Jovlunden, 2023) found that the process of filtering the population (GPW) data could not be completed on a computer with 4 GB RAM, IGPU and intel i3 processor. Using tried a computer with 48 GB of RAM, EGPU and intel i7, the filtering process succeeded. The successful completion of this process was therefore sensitive to the computational power available. The Marsden Moor casefile was set up using a similarly powerful machine, so this issue was not encountered.

8.2.2 Workflow data

Prior to the development of the GUI, a detailed analysis of the internal flow of information within the system was conducted. This was necessary to understand the scope of the information used within the system, establish what elements were affected, and better understand the order in which information impacted system performance. A schematic of the information flow is shown in Figure 46. Understanding this process supported the data types that needed to be captured within the GUI.

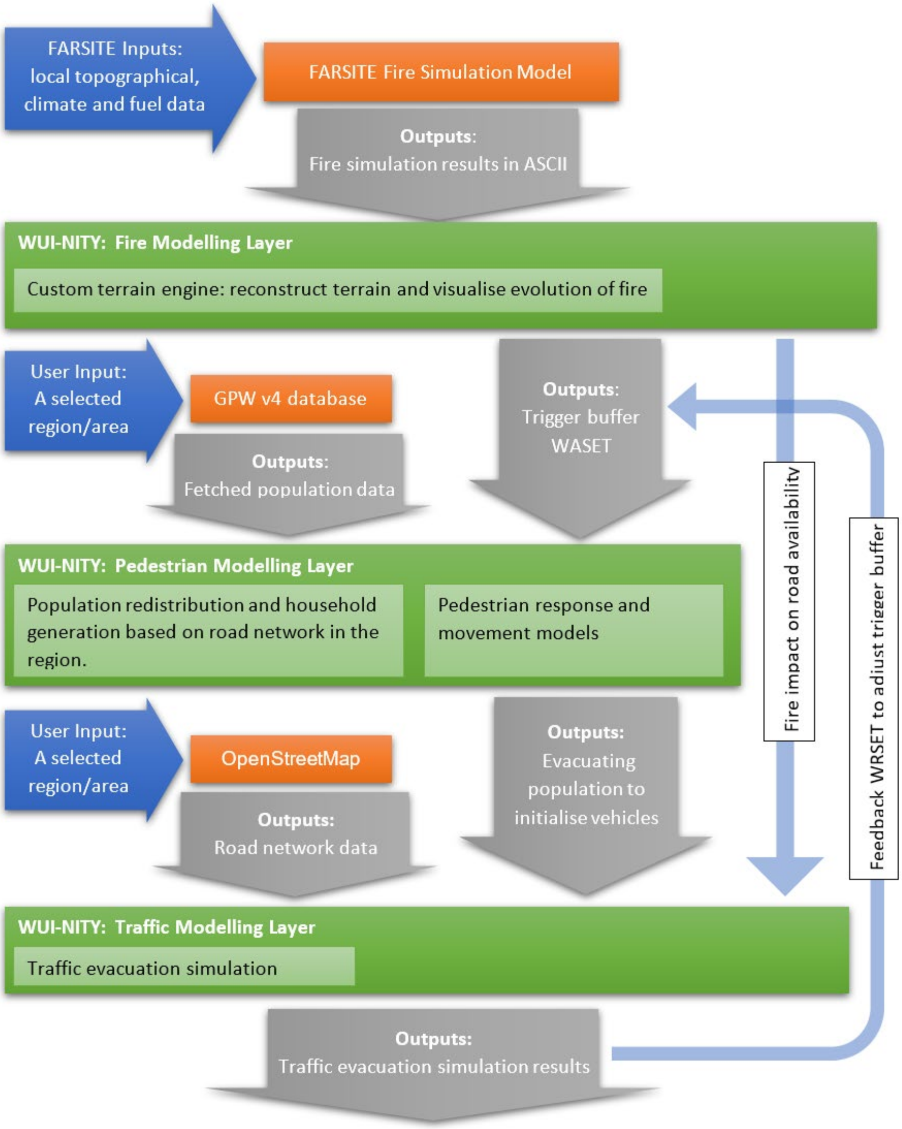


Figure 46. Data flow within WUI-NITY.

8.3 Design and implementation of Graphic User Interface enhancements

The WUI-NITY 2 base user-interface was further developed in WUI-NITY 3 to support the technical and functional steps of the workflow, in a left-hand panel, by the Lund University WUI-NITY development team. This UI does align with main blocks of workflow steps in the left-hand panel (as buttons), with context-specific UI elements appearing in the neighbouring right-hand area, as shown in Figure 47.

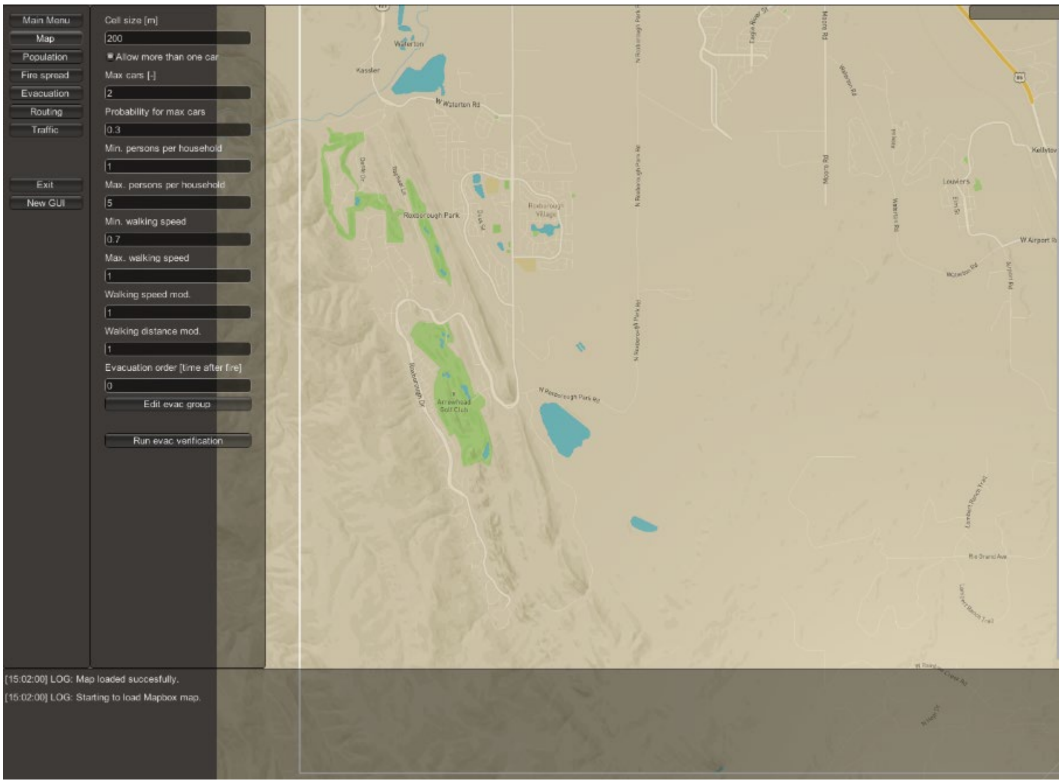


Figure 47. The core WUI-NITY interface, as developed within WUI-NITY 2.

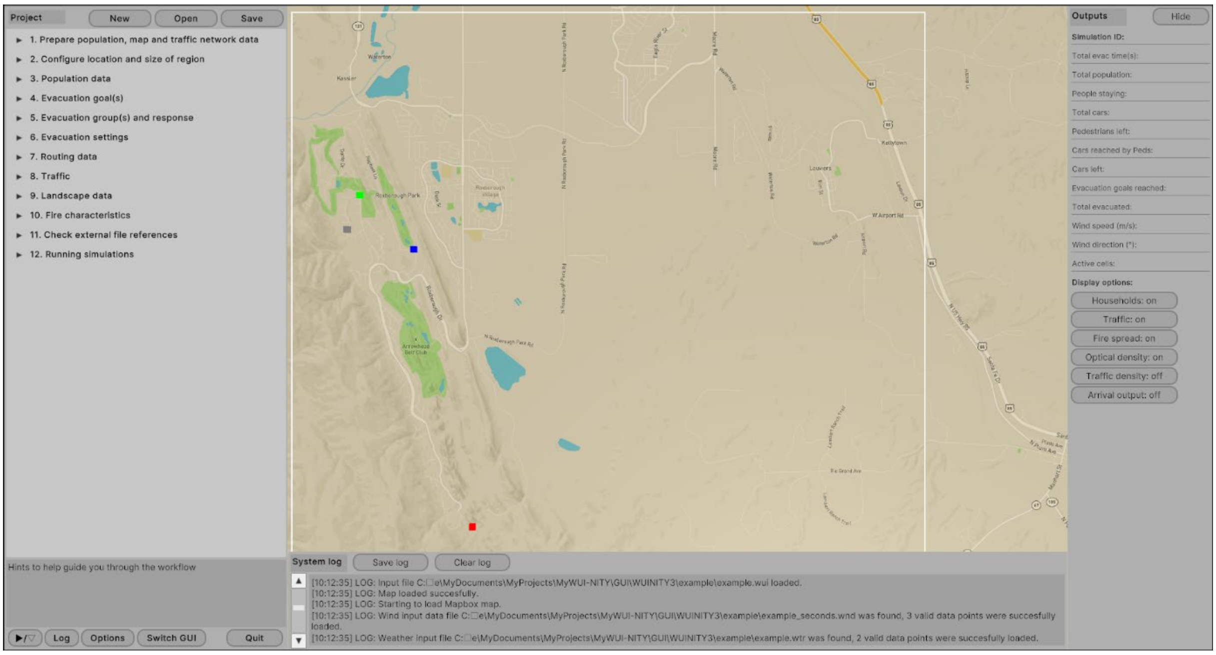


Figure 48. The new WUI-NITY 3 GUI as developed within WUI-NITY 3.

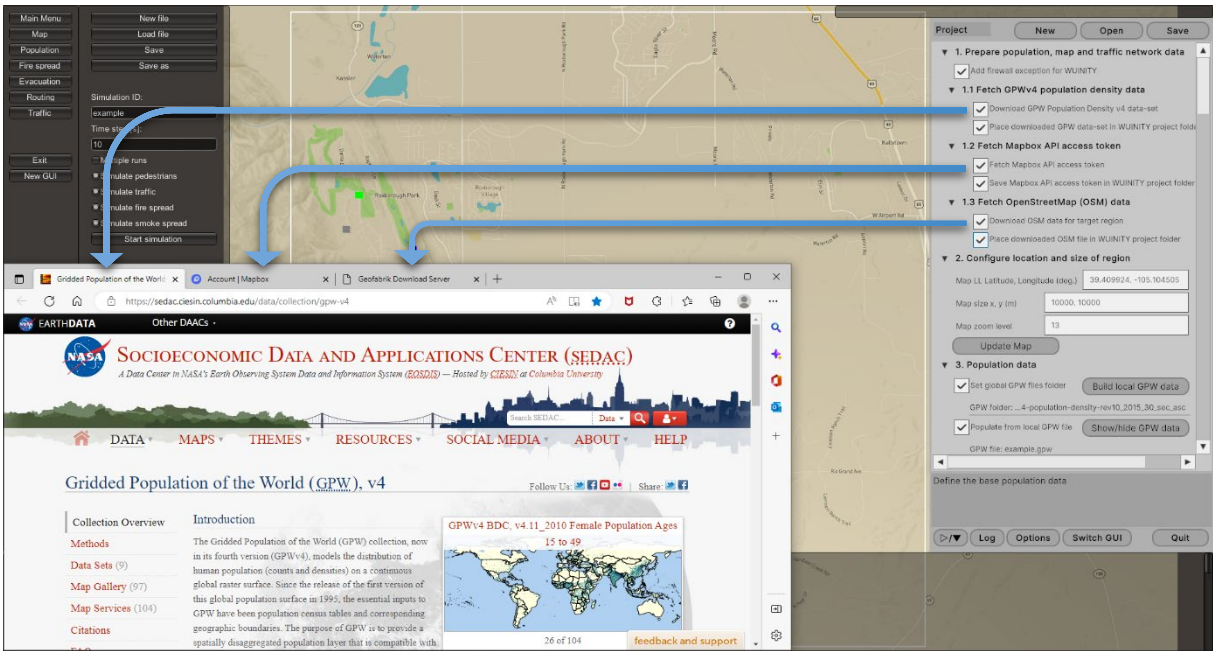


Figure 49. The WUI-NITY-3 workflow navigation panel docked on the right, launching the gridded population of the world, Mapbox access and OpenStreetMap websites directly from the UI panel element.

The vertical, expandable, and collapsible sections within the workflow navigator were built upon the base functional code in the pre-existing UI, following a similar order from top to bottom. The functional elements (edit-boxes etc.) were also built directly into the panel in the context of the headings of each section of the workflow (see Figure 48). In addition, as the user moves the mouse over each UI element, the textual "helper panel" contents are updated to provide some additional information to the user for each step along the way. In addition, where web data or external data sources are required, the interface starts up a browser window with the corresponding web resource, to support and help guide the user to gather items such as population and map data, as illustrated in Figure 49.

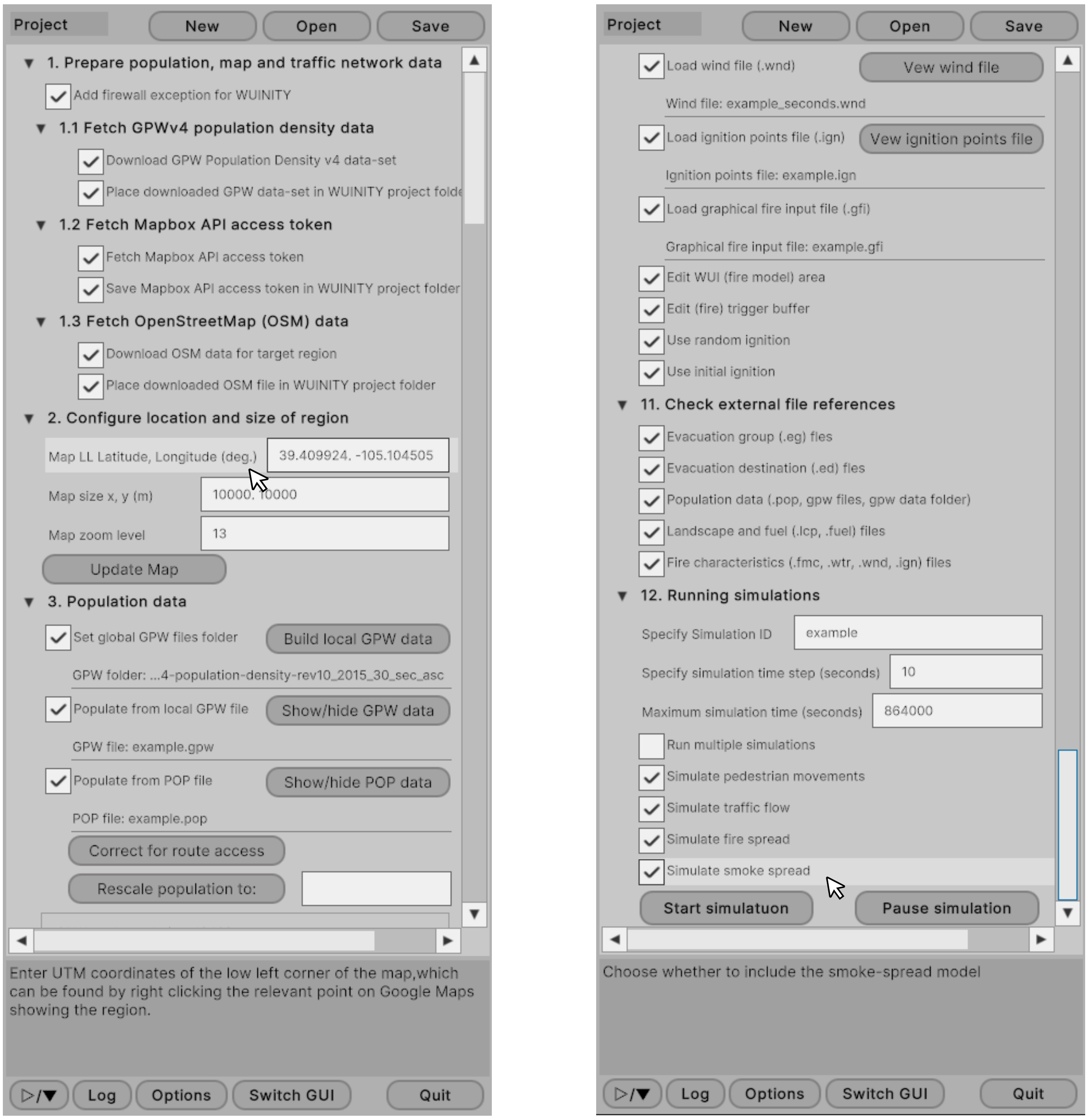


Figure 50. Workflow UI elements at the start (left) and end (right) in the vertical workflow panel.

Figure 50 show sample screen shots of the workflow 'start' and 'end' navigator elements. All these design elements are intended to guide the user from the start to the end of the workflow, explaining functionality as features and clickable items are hovered over by the user's mouse; displaying web pages or data where needed, and enabling the user to track progress throughout the workflow. In this way, the new interface encapsulates the required functionality, while reflecting a sequentially constructed, guided workflow for the user, where context-specific help is displayed automatically.

Note that the UI created is also intended to support future design iterations as WUI-NITY develops further, and the feature set is expanded, with more detailed help supplied during future developmental phases. The base specification file (the .uxml file) is in a form which can be edited by a technically-experienced user (not a trained software engineer). It was edited by a new arrival to the WUI-NITY team[25] through the workflow discovery phase, with some quick instruction from the Movement Strategy developers.

8.4 Test case - Marsden Moor, the UK

To test the effectiveness of the new GUI and verify the workflow developed, a 'test case' simulation was set up from scratch for a new region. The exercise was inspired by the Lund University efforts to set up a simulation in the Swedish landscape (Jovlunden, 2023) and the challenges encountered. It should be noted that the purpose of this exercise was not to conduct a rigorous scientific study of this region, rather, to select a general WUI region (not in America as the previous case study conducted with WUI-NITY in Roxborough Park (Ronchi et al., 2020)) to illustrate the usability and process of applying WUINITY in another geographical location using the workflow embedded within the GUI. This workflow test was carried out by a Movement Strategies consultant to augment the WUI-NITY team with an 'applied focus', rather than the core developers. The steps below are those followed as part of the model user following the workflow. In essence, these should match the nature and order of the workflow outlined in the GUI (see Section 8.1 to 8.3) and enable the model to be successfully applied.

The location of the test simulation was chosen to be Marsden Moor in the UK. Marsden Moor in West Yorkshire has been affected by several wildfires over recent years. It has been highlighted by news outlets drawing attention to fires at multiple times (such as the BBC in April 2021[26]) and it even has a dedicated "appeal page" on the UK National Trust website[27] because of the danger of wildfires during summers with low rainfall. As the location is outside of the United States, it also provides an opportunity to test the manual landscape (.lcp) file creation process, rather than using the readily available .lcps at LANDFIRE.

8.4.1 Data preparation

To build the Marsden Moor case, the following data was required:

- Global Population of the World (GPW data) (*Source: NASA via Columbia University*[28]*)*
- OpenStreetMap data *(Source: Geofabrik*[29]*)*
- Raster layers to create a landscape (.lcp) file
    - Elevation
    - Slope *(can be calculated from elevation if necessary)*
    - Aspect *(can be calculated from elevation if necessary)*
    - Canopy Cover
    - Fuel Model
- Wind *(used postulated values for Marsden case)*
- Weather *(used postulated values for Marsden case)*
- Fuel Moisture Content *(used postulated values for Marsden case)*

The topographic raster layers are often found at Earth Engine and Earth Explorer. Canopy cover and fuel models were obtained from the European Forest Fire Information System EFFIS[30]. Data availability varies by region due to the lack of surveying; this limits the available regions to model. In these cases, it is recommended to consult a local survey body for specialised data.

[25] Vai Saran
[26] https://www.bbc.com/news/uk-england-leeds-56884655
[27] https://www.nationaltrust.org.uk/support-us/appeals/marsden-moor-fires-appeal
[28] https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11/data-download
[29] *https://download.geofabrik.de/index.html*
[30] https://effis.jrc.ec.europa.eu/applications/data-and-services

8.4.2 The process of applying WUINITY to build the simulation case

The Marsden Moor case was built from scratch in 11 steps following the new workflow developed. All of the steps were verified in the new UI and completed successfully. The twelfth "step" was to finally run the simulation.

1. Prepared population, map and traffic network data [Setup basic folders and permissions]

- Downloaded the global GPW data sets and saved them in the WUINITY case folder: *[Created an account at https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11/data-download and downloaded the data sets]*
- Fetched OpenStreetMap data: *[The OSM data file for West Yorkshire region covering Marsden Moor (west-yorkshire-latest.osm.pbf) was downloaded from https://download.geofabrik.de]*

2. Configured location and size of region [Specify coordinates and extent of the target area]

- Specified map latitude and longitude *[Use UTM coordinates, found by right clicking the relevant point on Google Maps (Lat.: 53.5636281401421, Long.: -2.0196466373053). These coordinates determine the bottom left corner of the view]*
- Specified Map size (x, y) metres *[The default size, i.e. 10,000 m x10,000 m was selected]*
- Specified Map zoom level *[The default value 13 was chosen.]*

3. Configured population data [If necessary, there is an option to graphically edit custom populations directly from the map]

- Set global GPW folder *[Chose the global GPW folder downloaded from the Columbia.edu website and created a 'local GPW file']*
- Populated from local GPW *[This is the file created in the previous step. The result of this step created a .pop file in the same folder.]*
- Verified that the .pop file is present in the case folder *[Check the WUINITY project folder for an X.pop file. If not, the computer may lack sufficient hardware.]*

4. Configured evacuation goals [The location to which a population will evacuate]

- Identified evacuation goal(s) for the region and created evacuation goals files (.ed) accordingly. *[These files should be present within the 'Inputs' folder]*
- Entered goal attributes and coordinates in evacuation goals files *[Use UTM coordinates, found by right clicking the relevant point on Google Maps]*
- Loaded the evacuation goals files through UI and linked in the .wui files *[Open the .wui file to verify]*

5. Configured response curves and evacuation groups

- Created response curve files and entered the response probabilities as a function of time.
- Created evacuation groups files which define individual evacuation group with associated probabilities of adopting an evacuation goal and an evacuation curve.
- Loaded the response curve files and evacuation groups file into WUINITY.

6. Configured Evacuation settings [Specify the evacuation parameters to be modelled]

- Specified Cell size *[Specify evacuation area]*
- Allowed more than one car (toggle) *[Choose whether to allow more than one car per household]*

- Specified Max cars *[Choose the maximum number of cars per household]*
- Specified Probability for max. cars *[Choose the probability of the maximum number of cars per household]*
- Specified Min. persons per household *[Choose the minimum number of people per household]*
- Specified Max persons per household *Choose the maximum number of people per household]*
- Specified Min walking speed *[Unit: metres per second]*
- Specified Max walking speed *[Unit: metres per second]*
- Specified Evacuation order time [time after fire] *[Choose the number of minutes after the fire at which evacuation begins]*

7. Configured routing data [Setup routing data – redo this step if the location and size of region are modified]

- OSM -> routerdb: Built routing network database (.routerdb) from the downloaded OSM data file (.osm.pbf) *[For the Marsden Moor case, the downloaded data file for West Yorkshire region is west-yorkshire-latest.osm.pbf]*
- Built route collection file (.rc) from the routing network database (.routerdb) created from previous step.

8. Configured Traffic [Specify factors affecting movement of traffic]

- Specified Capacity speed *[This is the vehicle speed at max capacity]*
- Determined that Speed is affected by smoke *[Lowers traffic speed due to low visibility]*

9. Configured landscape files

[A landscape file must be compiled using GIS, unless the target area is within the US, in which case the LANDFIRE program will suffice]

- Addressed question: Is your target area within the United States? (Yes/No) *[For US locations, the LANDFIRE program contains all necessary topographical and fire characteristic layers]*
  - (If Yes) Use LANDFIRE to obtain an .lcp file, and proceed to next section *[Download an .lcp file for your target area from LANDFIRE Data Distribution Site[31]]*
  - (If No) Next step
- Downloaded slope, aspect and elevation data from Earth Explorer, Earth Engine or other source *[In a later part of the workflow, use of GIS may be necessary to scale the downloaded data to the same resolution as other data]*
- Downloaded a fuel data map from EFFIS or other source *[In a later part of the workflow, use of GIS may be necessary to scale the downloaded data to the same resolution as other data]*
- Downloaded canopy cover data from EFFIS or other source *[If the data is not available online, try contacting your local survey official]*
- Compiled the landscape file. Would you like to use Option 1 (QGIS) or Option 2 (ArcGIS)? *[QGIS/FlamMap is free, whereas ArcGIS is a paid program]*

  QGIS
  - Obtained elevation, canopy and fuel file

[31] https://www.landfire.gov/viewer/

- Made sure any base map used is set to EPSG:3857 WGS84
- Created and saved slope and aspect file from the elevation file, use the tools in Raster -> Analysis
- Drew a shapefile around your target area
- Enacted Geoprocessing Tools -> 'Clip' the elevation file to create a 'Clipped Extent' layer
- Set all raster layers to the same properties: use 'Save as' to change projection, change resolution and clip it to the 'clipped extent' layer [Ensure all layers are set to the same resolution]
- Downloaded FlamMap *[Download from https://www.firelab.org/media/994]*
- Opened FlamMap
- Clicked on: Landscape
- Clicked on Create Landscape file
- Inserted the geo-spatial data under 'required themes' *[These are the topographic, fuel and canopy data downloaded earlier]*
- Saved as an .lcp in the project folder *[You have now created a landscape file]*

ArcGIS

- Downloaded Arcfuels *[Download ArcFuels10 (firelab.org)]*
- Clicked on Build LCP -> Build LCP using Raster Data
- Added the needed raster images under 'Raster Data' *[These are the topographic, fuel and canopy data downloaded earlier]*
- Clicked on 'output'
- Used coordinates or another layer to define the LCP image boundaries *[Define the boundaries of your target area using UTM coordinates]*
- Clicked on Build LCP *[You have now created a landscape file]*

10. Identified fuel type attributes [Interpret fuel map data and modify other wildfire influencing factors according to your target location]

- Opened the fuel map in FlamMap, ArcGIS or QGIS *[This is the fuel map downloaded from EFFIS or other local source]*
- Identified the fuel type properties using one or more of the relevant fuel models *[The purpose of this step is to make sure that the fuels in the fuel map are represented in the .fuel file. View the 'properties' of the fuel map and refer to the following fuel models to identify the fuel attributes for each numbered entry: "1-13 Andersons original 13", "91-204 Scott and Burgan", "201-244 MSB:s Fire fuel mapping"]*
- Changed file attributes to match target landscape *[Open the following files using Notepad and edit the relevant parameters as necessary]*
    - Opened the .fuel file used by WUINITY and edit the fuel data *[Use the fuel property data identified in the previous step].*
    - Modified the fuel moisture code (.fmc) file [*Modify the fuel moisture code (humidity of shallow soil) according to your target area].*
    - Modified the location of where the fire will start (.ign) file [*Remember to use UTM coordinates].*

- Modified the temperature at different times during the simulation (.wtr) file *[Modify the .wtr file according to your target area].*
- Modified how the wind affects the spread of fire (.wnd) file *[Modify the .wnd file according to your target area].*

11. Checked file references [Opened the .wui file in a text editor (e.g. Notepad) and navigate to the relevant code blocks to verify whether the external files are referenced correctly]

- Population data (data sets in GPW data folder, .pop file, .gpw file)
- Evacuation groups (.eg) files
- Evacuation goals (.ed) files
- Response curves (.rsp) files
- Landscape and fuel (.lcp, .fuel) files *[Landscape file and fuel model]*
- Fire characteristic (.fmc, .wtr, .wnd, .ign) files *[Files related to propagation of fire*

12. Executed the simulation [Ensure relevant files are loaded and run the simulation]

- Specified Simulation ID *[Specified a Simulation ID for your desired simulation]*
- Specified Time step *[Specified the granularity of your desired simulation]*
- Multiple runs *[Specified the number of simulation iterations you wish to run]*
- Simulate ped *[Chose whether to simulate pedestrians]*
- Simulate traffic *[Chose whether to simulate traffic]*
- Simulate fire spread *[Chose whether to simulate fire spread]*
- Simulate smoke spread *[Chose whether to simulate smoke spread]*
- Run simulation

8.4.3 Simulation settings and outputs

The area immediately surrounding Marsden town was chosen to be simulated – the following sub-sections contain the assumptions involved in the modelling process and a description of possible outputs:

- Evacuation objective and assumptions
- Evacuation and Traffic Settings
- Outputs

Set evacuation objective and assumptions

In the simulated area shown in Figure 51, Marsden and Slaithwaite are the major population centres. Figure 52 shows an estimate of the population density in this area based on the GPW data.

- The three chosen evacuation destinations are situated in an arc outside of the towns.
- The fire ignition point was chosen to lie south-east of Marsden, such that residents can evacuate away from the fire.
- Since there was no real data collected concerning fire characteristic in this region, we used the same inputs from the Roxborough Park case study (Ronchi et al., 2020).
- Slaithwaite, Marsden and the evacuation destinations are connected by a network of A-roads (A640 and A62) and several B-roads.

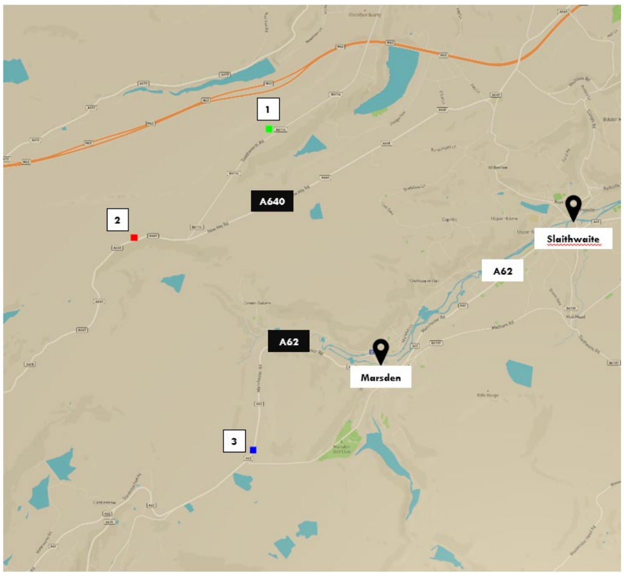


Figure 51. Evacuation destinations and traffic routes around Marsden and Slaithwaite population centres.

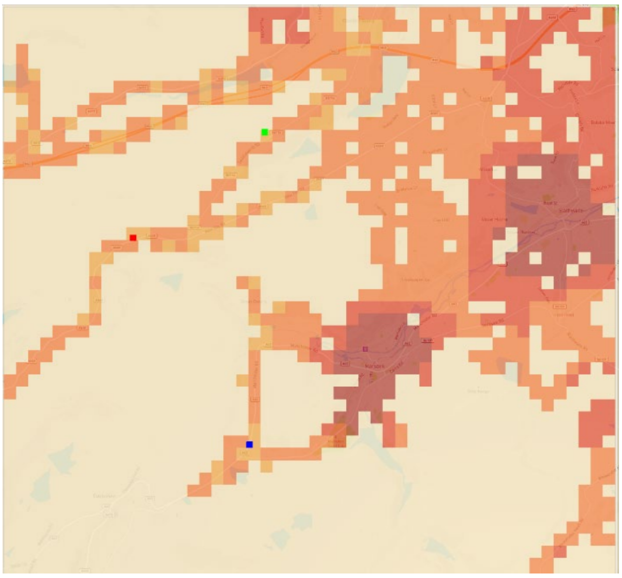


Figure 52. The raw population data for the selected region at Marsden Moor showing the distribution of 16,017 people.

Configured evacuation and traffic settings
The following evacuation and traffic parameters were applied to the simulation, shown in Figures 53.

- Cell size
- More than one car per household allowed
- Maximum number of cars per household
- Probability of maximum number of cars per household
- Minimum number of persons per household
- Maximum number of persons per household
- Minimum walking speed
- Maximum walking speed
- Walking distance modulus (redundant placeholder metric)
- Walking speed modulus (redundant placeholder metric)

- Capacity speed (traffic speed at full road capacity)
- Traffic speed is not affected by smoke

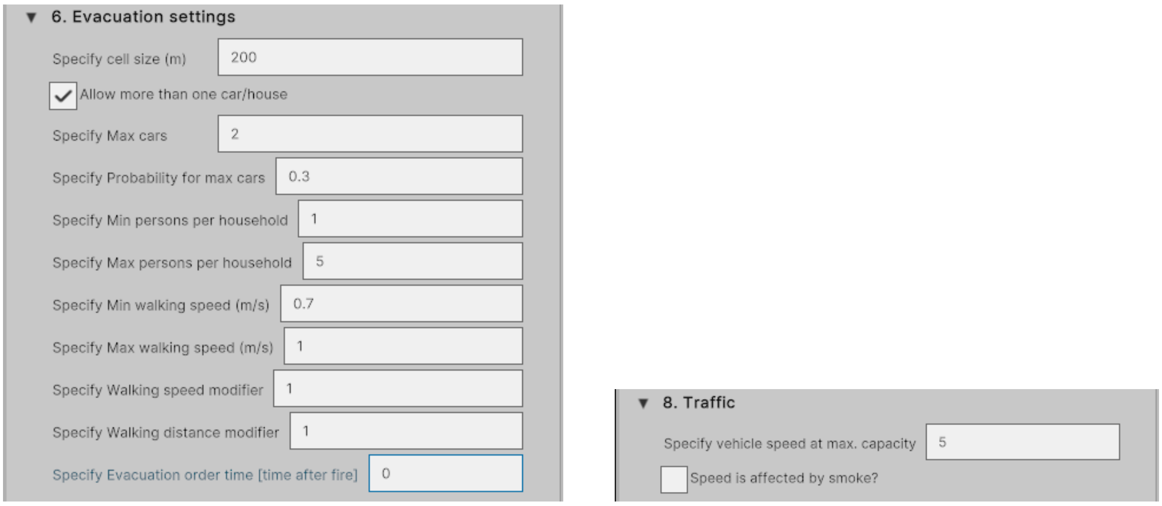


Figure 53. Evacuation parameters (left) and Traffic simulation parameters (right).

Generated outputs

WUI-NITY was then executed and generated outputs. As part of this, WUINITY auto-created an 'output' folder and populated it with 'pedestrian output' and 'traffic output' .csv files. The outputs contained in each .csv file are summarised below.

Pedestrian output per time:

- Time (s) *[the 'time step' interval specified before the model run]*
- Households left *[the total number of households from which people have NOT started evacuation]*
- People left *[the total number of people that have NOT started evacuation]*
- Households started moving *[the total number of households that have started evacuation]*
- People started moving *[the total number of people that have started evacuation]*
- Households reached car *[the total number of households whose residents have reached their cars]*
- People reached car *[the total number of people that have reached their cars]*
- Total cars *[the total number of evacuating cars in the simulation]*
- Average walking distance *[The average walking distance of an evacuation person]*

Traffic output per time.

- Time (s) *[the 'time step' interval specified before the model run]*
- Injected cars *[the total number of cars that started evacuating in the given time interval]*
- Exiting cars *[the total number of cars that reached their destination in the given time interval]*
- Current cars in system *[the total number of evacuating cars in the system]*
- Exiting people *[the total number of drivers/passengers that reached their destination in the given time interval]*
- Average vehicle speed (km/h) *[the average speed of an evacuating car]*
- Minimum vehicle speed (km/h) *[the minimum speed of an evacuating car]*
- Number of cars that have reached each evacuation goal *[the number of cars that have reached each evacuation goal]*

This task was completed successfully, and these outputs were in accordance with expectation. These outputs are currently generated and stored outside of the model. In future GUI iterations, the GUI will be enhanced to capture the output and present some aspects of it within the model GUI – accounting for new user(s) and upcoming functionality.

Once these steps were completed, the model was then executed. The model was able to simulate the movement of the residents as specified (see Figure 54). The output demonstrates that the workflow appears to aid the user in the model configuration – at least for the test case. The workflow design was iterated where clarifications were required during the process with lessons being learned regarding the language used and references to specific GUI interactions.

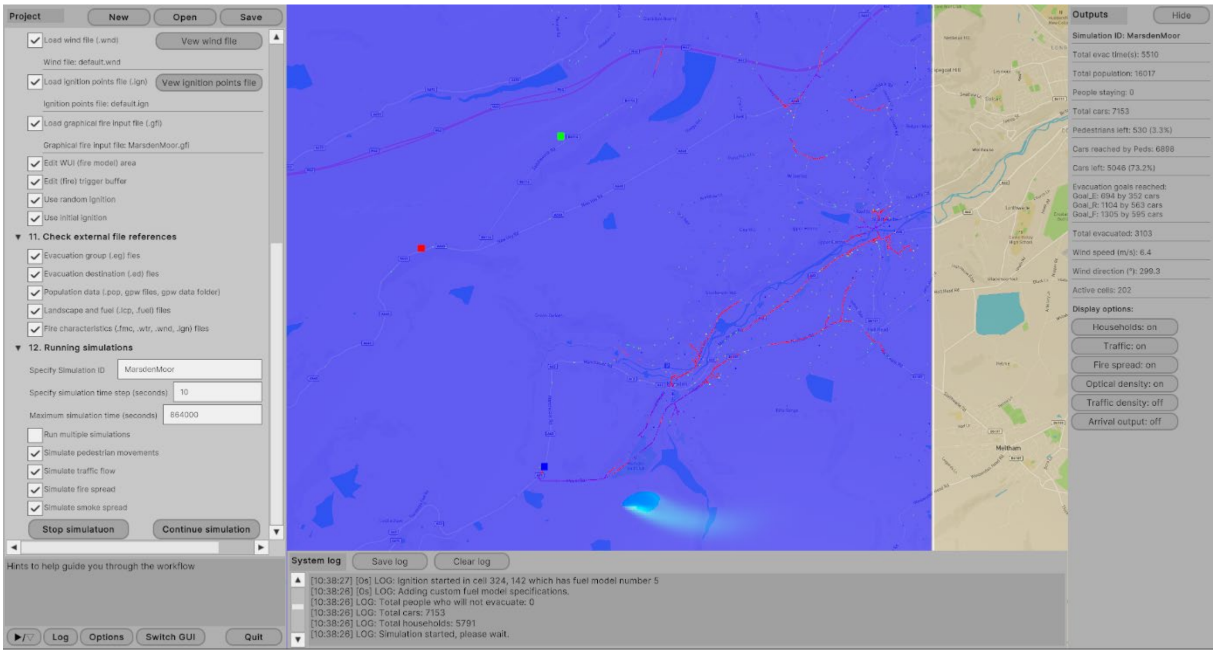


Figure 54. Example output from Marsden Moor application running within the new GUI.

Therefore, two key outcomes were achieved during this test case:

- The user was able to interpret and apply the workflow as outlined.
- The application of the workflow allowed the model to simulate the scenario as specified and produce output.

8.5 Summary of GUI and workflow development

The primary objective of the GUI work discussed here was to enhance the reliability and usability of the model both for expert and new users. In both cases, it is assumed that a user has an understanding of the wildfire evacuation and the general capabilities of the model. Considerable progress has been made.

Given the range of user types that might be interested in using the model – ranging from researcher to practitioner – it was important to ensure a level of consistency in its use. The approach adopted includes the provision of a workflow. This was to shape the order in which key tasks were completed and ensure that the user modified core elements of the model to reflect their scenario of interest (i.e. to prevent the user accidentally using a model default). The model is sensitive to the order in which information is provided and this providing a simple guide within the GUI via the workflow should reduce errors.

The development of this workflow was performed by the research team at Movement strategies along with inputs from within the development team at Lund University and the rest of the WUI-NITY research team. This input proved user given the different perspectives shown and having the model applied to test cases during the development ensuring real-world feedback.

The expert user can still operate independently of the GUI – allowing them more direct / text-based access to the internal workings of the model. Such users can still configure the numerous input files manually, allowing quick access for experienced users. However, even for these users, the GUI changes will have simplified the uploading and editing of these files into the model.

The GUI development is very much an ongoing task – that needs to reflect changes to the model application, new user requirements, new model functionality and developments in the workflow. Future work will certainly include:

- Developing WUI-NITY guidance to reflect the new GUI design and its use.
- Improving the interface for generating and managing model output. The current focus of the work presented here has been on the user *configuring* the model – providing inputs into the model. This was necessary as the previous GUI was primarily a research design. Therefore, this aspect needed to be updated to account for a broader user base that included practitioners. The GUI output process also needs equivalent development – so the wraparound experience is consistent. However, to some degree, the GUI reflecting the output will need to be addressed as the functionality evolves and the model output expands. The current model functionality can still be accommodated; however, the GUI will evolve to do so adopting the same workflow approach and to better reflect both the user and functionality developments.
- Given developments in both the model, data access and computational resources, the potential for batch operation is now feasible. The current GUI has been developed with this capability in mind, such that the introduction of a batch control – configuring the initial conditions of a set runs – should be relatively simple. This capability would enable probabilistic approaches to be more effectively applied – generating a more stochastic basis for the output produced.

9. Conclusions

The WUI-NITY3 project addressed a set of known challenges in the domain of wildfire evacuation modelling. In particular, given the need for more data regarding traffic movement during emergency response, it provides tool and data sets to enhance model development and validation. Several research efforts have been carried out to improve the availability for wildfire evacuation models and improve the capabilities and applications of WUI-NITY.

A methodology has been presented for traffic evacuation data extraction, making use of the Caltrans Performance Measurement System (PeMS) database to demonstrate its applicability. In this context, a freely available tool, the Traffic Data Analyser (TDA) was released to facilitate the extraction of traffic data from such databases. In parallel, two data sets from actual fires, the 2020 Glass fire and the 2020 Silverado Fire were made available in open access for any interested party[32]. Those data sets can be used by any researcher or user interested in wildfire evacuation and for different purposes (validation, development, etc.).

The use of Virtual Reality technology was also explored to study traffic evacuation movement variables which cannot be systematically investigated from real-world databases. The example in this work relates to the information provided by variable message signs and foundations were laid for the study of several other variables of potential interest. VR was here intended as a tool to complement other modes of data collection.

Recent improvements in trigger buffer modelling through the k-PERIL tool were presented, aiming at transitioning towards stochastic trigger modelling integrated into WUI-NITY.

The WUI-NITY tool was fed with the new data and knowledge obtained during the WUI-NITY 3 project in order to improve its accuracy and expand its predictive capabilities.

Finally, the graphical user interface (GUI) of the model was improved to ensure that WUI-NITY can become accessible to a wider range of users. This was also facilitated by detailing the WUI-NITY application workflow.

[32] https://doi.org/10.5281/zenodo.7500333 and https://doi.org/10.5281/zenodo.7483487

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Appendix 1. Reported accidents in case studies

This section reports the accidents in the case studies under consideration (2020 Glass Fire and 2020 Silverado Fire).

Reported accidents in the Glass Fire

Table A1.1. Reported incidents on US101 in Sonoma County during the evacuation period. Only with a duration longer than 5 minutes

Time (mm-dd-yy hh:mm)	Duration (minutes)	Post-mile	Location	Description
09-01-20 01:09	55	470.9	Us101 S - Petaluma Blvd S Ofr	CFIRE-Car Fire
09-28-20 00:41	131	493.3	Us101 N - River Rd Ofr	1183-Trfc Collision-Unkn Inj
09-28-20 03:55	94	479.2	Us101 N - Railroad Ave Ofr	1125-Traffic Hazard
09-28-20 06:12	35	470.9	Us101 S - Petaluma Blvd S Ofr	1179-Trfc Collision-1141 Enrt
09-28-20 08:02	16	475.6	Us101 S - Petaluma Blvd N Onr	1182-Trfc Collision-No Inj
09-28-20 08:04	13	475.6	Us101 S - Petaluma Blvd N Onr	1182-Trfc Collision-No Inj
09-28-20 09:21	15	475.8	Us101 S - Petaluma Blvd N Ofr	1183-Trfc Collision-Unkn Inj
09-28-20 09:22	14	475.8	Us101 S - Petaluma Blvd N Ofr	1183-Trfc Collision-Unkn Inj
09-28-20 13:29	70	470.9	Us101 S - Petaluma Blvd S Ofr	1125-Traffic Hazard
09-28-20 13:42	6	475.7	Us101 S - Penngrove Onr	1125-Traffic Hazard
09-28-20 14:41	47	490.9	Us101 N - Bicentennial Wy Ofr	1125-Traffic Hazard
09-28-20 17:04	50	516.4	Us101 N - Asti Ofr	1183-Trfc Collision-Unkn Inj
09-28-20 19:48	19	484.6	Us101 S - Todd Rd Onr	1125-Traffic Hazard

09-29-20 15:51	11	507.0	Lytton Springs Rd Ofr - Us101 S	1182-Trfc Collision-No Inj
09-29-20 20:20	24	473.6	Us101 N - E Washington St W Onr	1125-Traffic Hazard
09-30-20 01:26	33	479.2	Us101 N - Railroad Ave Ofr	1182-Trfc Collision-No Inj
09-30-20 07:50	22	484.0	Us101 N - Santa Rosa Ave Ofr	1182-Trfc Collision-No Inj
09-30-20 15:10	19	501.5	Us101 S - Healdsburg Ave	WW-Wrong Way Driver
09-30-20 16:36	77	496.1	Us101 N - Shiloh Rd Ofr	20002-Hit and Run No Injuries
09-30-20 17:43	93	476.2	Us101 N - Penngrove Ofr	1183-Trfc Collision-Unkn Inj
09-30-20 17:44	34	476.2	Us101 N - Penngrove Ofr	1183-Trfc Collision-Unkn Inj
09-30-20 22:16	41	485.1	Us101 N - Todd Rd Ofr	1183-Trfc Collision-Unkn Inj

Table A1.2. Reported incidents on US101 in Sonoma County, CA from the 12th to the 13th of October 2020 with a duration longer than 5 minutes (R1).

Time (mm-dd-yy hh:mm)	Duration (minutes)	Post-mile	Location	Description
09-01-20 01:09	55	470.9	Us101 S - Petaluma Blvd S Ofr	CFIRE-Car Fire
09-01-20 05:43	96	493.2	Us101 S - River Rd Ofr	1179-Trfc Collision-1141 Enrt
09-01-20 07:50	16	490.9	Us101 N - Bicentennial Wy Ofr	1125-Traffic Hazard
09-01-20 08:49	99	470.4	Us101 S - Petaluma Blvd S Onr	20002-Hit and Run No Injuries
09-01-20 17:10	23	473.5	Us101 N - E Washington St Onr	1183-Trfc Collision-Unkn Inj

09-01-20 21:32	22	490.2	Us101 N - Steele Ln Ofr	1125-Traffic Hazard
09-02-20 05:57	33	471.0	Petaluma Blvd S Ofr - Us101 N	1182-Trfc Collision-No Inj
09-02-20 08:33	25	473.3	Us101 N - E Washington St Ofr	1125-Traffic Hazard
09-02-20 18:54	689	475.7	Us101 S - Penngrove Onr	1179-Trfc Collision-1141 Enrt
08-31-20 06:59	19	485.1	Us101 N - Todd Rd Ofr	1125-Traffic Hazard
08-31-20 08:42	31	483.0	Us101 N - Rohnert Park W Onr	1125-Traffic Hazard
08-31-20 14:06	11	471.6	US101 N - PETALUMA BLVD S ONR	1182-Trfc Collision-No Inj
08-31-20 14:55	16	499.2	Us101 S - Arata Ln Ofr	FIRE-Report of Fire
08-31-20 15:56	13	499.0	Us101 S - Arata Ln Onr	1166-Defective Traffic Signals
08-31-20 17:07	23	472.4	Us101 N - Lakeville Hwy Ofr	1125-Traffic Hazard
08-31-20 17:09	27	472.4	Us101 N - Lakeville Hwy Ofr	1125-Traffic Hazard
08-31-20 21:29	23	470.9	Us101 S - Petaluma Blvd S Ofr	1125-Traffic Hazard
09-14-20 04:31	66	490.1	Us101 S - Steele Ln Ofr	1179-Trfc Collision-1141 Enrt
09-14-20 18:43	658	511.9	Us101 N - Canyon Rd Ofr	CZP-Assist with Construction
09-14-20 21:39	28	491.2	Us101 S - Hopper Ave Onr	1125-Traffic Hazard
09-15-20 08:45	10	518.9	Us101 S - S Cloverdale Blvd Ofr	DOT-Request CalTrans Notify
09-15-20 09:45	19	482.3	Us101 S - Rohnert Park Ofr	1125A-Animal Hazard
09-15-20 10:22	8	487.5	US101 N - SANTA ROSA AVE OFR	1125-Traffic Hazard

09-15-20 11:05	30	472.4	Us101 N - Lakeville Hwy Ofr	1125-Traffic Hazard
09-15-20 11:55	9	490.2	Us101 N - Steele Ln Ofr	1125-Traffic Hazard
09-15-20 13:16	86	490.1	Us101 S - Steele Ln Ofr	23114-Object Flying From Veh
09-15-20 14:14	40	488.1	Us101 S - Us101 S Sr12 Con	1125-Traffic Hazard
09-15-20 15:47	32	489.3	Us101 N - College Ave Ofr	1125-Traffic Hazard
09-15-20 16:19	30	485.1	Us101 N - Todd Rd Ofr	1183-Trfc Collision-Unkn Inj
09-15-20 16:21	68	485.1	Us101 N - Todd Rd Ofr	1179-Trfc Collision-1141 Enrt
09-16-20 01:31	25	490.1	Us101 S - Steele Ln Ofr	1182-Trfc Collision-No Inj
09-16-20 02:23	40	495.2	Us101 N - Airport Blvd Onr	1182-Trfc Collision-No Inj
09-16-20 13:08	6	471.0	Us101 N - Petaluma Blvd S Ofr	1125-Traffic Hazard
09-16-20 21:45	100	471.8	Us101 S - Lakeville Hwy Onr	1125-Traffic Hazard
09-21-20 04:17	40	490.1	Us101 S - Steele Ln Ofr	1183-Trfc Collision-Unkn Inj
09-21-20 06:28	709	511.9	Us101 N - Canyon Rd Ofr	CZP-Assist with Construction
09-21-20 08:07	6	490.7	Us101 N - Steele Ln Onr	1125-Traffic Hazard
09-21-20 13:33	11	486.3	Hearn Ave Onr - Us101 S	1125-Traffic Hazard
09-21-20 13:37	50	472.0	Us101 S - Lakeville Hwy Ofr	1182-Trfc Collision-No Inj
09-21-20 13:52	15	485.1	Us101 N - Todd Rd Ofr	1125-Traffic Hazard
09-21-20 14:50	51	503.0	Us101 N - Cntrl Healdsburg Ofr	1125-Traffic Hazard

09-21-20 15:04	11	489.3	Us101 N - College Ave Ofr	1183-Trfc Collision-Unkn Inj
09-21-20 15:33	19	495.9	Us101 S - Shiloh Rd Ofr	1183-Trfc Collision-Unkn Inj
09-21-20 15:42	14	473.6	Us101 N - E Washington St W Onr	1125-Traffic Hazard
09-21-20 16:27	12	486.9	Us101 N - Hearn Ave Ofr	1125-Traffic Hazard
09-21-20 16:40	9	480.5	Us101 N - W Sierra Ave Ofr	1125-Traffic Hazard
09-21-20 17:00	43	522.7	Us101 N - Old Redwood Hwy Onr	CFIRE-Car Fire
09-21-20 17:26	17	486.8	Us101 S - Baker Ave Onr	1182-Trfc Collision-No Inj
09-22-20 06:22	1,392	511.9	Us101 N - Canyon Rd Ofr	CZP-Assist with Construction
09-22-20 10:06	8	471.6	Us101 N - Petaluma Blvd S Onr	1125-Traffic Hazard
09-22-20 11:35	22	482.6	Us101 S - Golf Course Dr Onr	1125-Traffic Hazard
09-22-20 13:03	14	502.0	Healdsburg Ave Ofr - Us101 N	1125-Traffic Hazard
09-22-20 15:37	50	504.7	Us101 N - Dry Creek Rd Ofr	1125-Traffic Hazard
09-22-20 16:41	46	485.1	Us101 N - Todd Rd Ofr	1179-Trfc Collision-1141 Enrt
09-22-20 16:42	32	485.1	Us101 N - Todd Rd Ofr	1179-Trfc Collision-1141 Enrt
09-22-20 16:50	13	484.8	Us101 S - Todd Rd Ofr	1125-Traffic Hazard
09-22-20 16:54	9	492.9	Us101 S - River Rd	1125-Traffic Hazard
09-22-20 22:49	13	521.4	Us101 S - Old Redwood Hwy Onr	WW-Wrong Way Driver
09-22-20 22:50	181	475.8	Us101 S - Petaluma Blvd N Ofr	1183-Trfc Collision-Unkn Inj

09-23-20 09:24	7	504.7	Us101 N - Dry Creek Rd Ofr	1125-Traffic Hazard
09-23-20 14:29	44	488.6	Us101 N - Sr12 Us101 N Con	FIRE-Report of Fire
09-23-20 14:34	25	475.8	Us101 S - Petaluma Blvd N Ofr	1125-Traffic Hazard
09-23-20 14:37	35	493.3	Us101 N - River Rd Ofr	1125-Traffic Hazard
09-23-20 20:52	15	472.9	Us101 S - E Washington St Ofr	WW-Wrong Way Driver

Reported accidents in the Silverado Fire

Table A1.3. Reported incidents on I-5 in Orange County, CA from the 12th to the 13th of October 2020 with a duration longer than 5 minutes (R1).

Start Time	Duration (mins)	Post-mile	LOCATION	DESCRIPTION
10-12-20 13:08	64	99.9	I5 N - Jamboree Rd	1125-Traffic Hazard
10-12-20 13:22	15	97.3	I5 N - Jeffrey Rd	1125-Traffic Hazard
10-12-20 15:08	24	88.8	I5 N - La Paz Rd Lp	1125-Traffic Hazard
10-12-20 15:05	20	88.8	I5 N - La Paz Rd Lp	1125-Traffic Hazard
10-12-20 16:10	133	99.5	I5 N - JAMBOREE RD OFR	1125-Traffic Hazard
10-12-20 16:49	15	104.8	I5 N - 17th St E Onr	1125-Traffic Hazard
10-12-20 17:02	71	104.8	I5 N - 17th St E Onr	1125-Traffic Hazard
10-12-20 18:04	18	90.6	I5 N - El Toro Rd Ofr	1182-Traffic Collision-No Inj[33]
10-12-20 18:37	25	87.5	I5 N - Oso Pkwy	20002-Hit and Run No Injuries
10-12-20 22:40	21	93.6	I5 N - I405	1125A-Animal Hazard
10-12-20 22:52	71	91	I5 N - El Toro Rd E Onr	1125-Traffic Hazard
10-13-20 09:53	66	99.9	I5 N - Jamboree Rd E Onr	1182- Traffic Collision-No Inj
10-13-20 09:58	9	99.9	I5 N - Jamboree Rd	1182- Traffic Collision-No Inj
10-13-20 10:21	117	91	I5 N - El Toro Rd	1179- Traffic Collision-1141 Enrt[34]

[33] "Inj"= Injuries
[34] "Enrt"= Enroute

10-13-20 10:19	119	89.7	I5 N - Alicia Pkwy	1125-Traffic Hazard
10-13-20 10:27	237	91	I5 N - El Toro Rd	1179- Traffic Collision-1141Enrt
10-13-20 10:34	58	89.7	I5 N - ALICIA PKWY	1125-Traffic Hazard
10-13-20 10:36	52	91	I5 N - El Toro Rd	SIGNAL Alert
10-13-20 10:54	40	102.5	I5 N - SR55	1183- Traffic Collision-Unknown Inj
10-13-20 17:07	6	102.8	I5 N - Main St	1182- Traffic Collision-No Inj
10-13-20 17:09	92	102.8	I5 N - Main St	1182- Traffic Collision-No Inj
10-13-20 17:05	55	104.4	I5 N - 17th St Ofr	1179- Traffic Collision-1141 Enrt
10-13-20 23:55	9	102.5	I5 N To - Sr55 N Con	20002-Hit and Run No Injuries
10-12-20 06:17	93	87.4	I5 S - Oso Pkwy	1182- Traffic Collision-No Inj
10-12-20 07:44	39	86	I5 S - Crown Valley Pkwy Cv	1182- Traffic Collision-No Inj
10-12-20 12:28	37	102.2	I5 S - Sr55 N I5 S Con	1125-Traffic Hazard
10-12-20 13:12	23	86	I5 S - Crown Valley Pkwy Cv	1183- Traffic Collision-Unknown Inj
10-12-20 13:07	6	88.7	I5 S - La Paz Rd	1182- Traffic Collision-No Inj
10-12-20 15:13	21	100.4	I5 S - TUSTIN RANCH RD	1125-Traffic Hazard
10-12-20 15:18	26	100.4	I5 S - TUSTIN RANCH RD	1125-Traffic Hazard
10-12-20 15:47	36	98.8	I5 S - CULVER DR	1125-Traffic Hazard
10-12-20 15:58	8	97.2	I5 S - Jeffrey Rd	1125-Traffic Hazard
10-13-20 08:04	36	104.7	I5 S - 17th St	1182- Traffic Collision-No Inj
10-13-20 08:58	12	102	I5 S - Sr55 S I5 S Con	1182- Traffic Collision-No Inj
10-13-20 14:09	63	86	I5 S - Crown Valley Pkwy Cv	1179- Traffic Collision-1141 Enrt
10-13-20 18:42	19	89.7	I5 S - Alicia Pkwy	1125-Traffic Hazard
10-13-20 18:40	19	89.7	I5 S - Alicia Pkwy	1125-Traffic Hazard
10-13-20 20:13	10	104	I5 S - Grand Ave	1125-Traffic Hazard

Table A1.4. Reported incidents on I-5 in Orange County, CA from the 19th to the 20th of October 2020 with a duration longer than 5 minutes (R2).

Start Time	Duration (mins)	Post-mile	LOCATION	DESCRIPTION
10-19-20 00:10	54	95.2	I5 N - I5 N Sr133 N Con	1125-Traffic Hazard
10-19-20 09:53	33	102.8	I5 N - Main St	FIRE-Report of Fire
10-19-20 14:12	10	84.8	I5 N - Sr73	1125-Traffic Hazard
10-19-20 17:02	18	99.9	I5 N - Jamboree Rd	1182--Traffic Collision-No Inj
10-19-20 17:07	7	99.9	I5 N - Jamboree Rd	1182- Traffic Collision-No Inj
10-19-20 17:58	101	84.8	I5 N - Sr73	1125-Traffic Hazard
10-19-20 22:04	72	93.4	I5 N - I405 N	1125-Traffic Hazard
10-20-20 06:56	12	103.2	I5 N - 1st St	1125-Traffic Hazard
10-20-20 14:24	33	96.5	Sand Canyon Av Onr - I5 N	1125-Traffic Hazard
10-20-20 14:58	8	93.1	I5 N - Bake Pkwy	1125-Traffic Hazard
10-20-20 15:37	11	98.1	I5 N - YALE AVE	1183- Traffic Collision-Unknown Inj
10-20-20 18:46	10	104.7	I5 N - 17th St	1183- Traffic Collision-Unknown Inj
10-20-20 20:43	14	94.5	I5 N - Alton Pkwy	20001-Hit and Run w-Injuries
10-19-20 06:02	113	98.8	I5 S - Culver Dr	1125-Traffic Hazard
10-19-20 08:55	8	92.1	I5 S - Lake Forest Dr	1125-Traffic Hazard
10-19-20 08:53	6	92.1	I5 S - Lake Forest Dr	1125-Traffic Hazard
10-19-20 10:06	23	86	I5 S - Crown Valley Pkwy Cv	1125-Traffic Hazard
10-19-20 12:38	122	85.1	I5 S - Avery Pkwy	1125-Traffic Hazard
10-19-20 16:39	6	94.8	I5 S - Barranca Pkwy	CFIRE-Car Fire
10-19-20 16:38	24	95.6	I5 S - I5 S Sr133 S Con	CFIRE-Car Fire
10-19-20 22:31	372	88.7	I5 S - La Paz Rd Lp	-Assist with Construction
10-20-20 14:46	8	87.4	I5 S - Oso Pkwy	1125-Traffic Hazard
10-20-20 14:56	10	94.8	I5 S - Barranca Pkwy	1125-Traffic Hazard
10-20-20 14:55	46	87.4	I5 S - Oso Pkwy	1125-Traffic Hazard
10-20-20 17:07	24	85.1	I5 S - Avery Pkwy	1182- Traffic Collision-No Inj

10-20-20 17:05	53	85.1	I5 S - Avery Pkwy	1182- Traffic Collision-No Inj
10-20-20 19:20	63	87.4	I5 S - Oso Pkwy	1182- Traffic Collision-No Inj
10-20-20 19:31	100	101	I5 S - Red Hill Ave Onr	1125-Traffic Hazard

Table A1.5. Reported incidents on I-5 in Orange County, CA from the 26th to the 27th of October 2020 with a duration longer than 5 minutes (E).

Start Time	**Duration (mins)**	**Post-mile**	**LOCATION**	**DESCRIPTION**
10-26-20 06:02	13	93.4	I5 N To - I405 N Con	1125-Traffic Hazard
10-26-20 06:07	7	93.4	I5 N To - I405 N Con	1125-Traffic Hazard
10-26-20 09:54	17	95.5	I5 N - SR133	1184-Req California Highway Patrol Traffic Control
10-26-20 11:17	22	92.2	I5 N - Lake Forest Dr	1125-Traffic Hazard
10-26-20 11:16	23	92.2	I5 N - Lake Forest Dr	1125-Traffic Hazard
10-26-20 12:31	11	96.2	I5 N - SAND CANYON RD	1125-Traffic Hazard
10-26-20 16:01	17	103.2	I5 N - E 1st St	20002-Hit and Run No Injuries
10-26-20 17:01	11	87.5	I5 N - Oso Pkwy	1125-Traffic Hazard
10-26-20 17:21	17	97.3	I5 N - Jeffrey Rd	1125-Traffic Hazard
10-27-20 05:58	34	103.1	I5 N - 4th St Ofr	1183- Traffic Collision-Unknown Inj
10-27-20 05:55	37	103.1	I5 N - 4th St Ofr	1183- Traffic Collision-Unknown Inj
10-27-20 06:11	9	100.5	I5 N - TUSTIN RANCH RD	1125-Traffic Hazard
10-27-20 08:04	6	99.9	I5 N - Jamboree Rd	1125-Traffic Hazard
10-27-20 08:03	9	99.9	I5 N - Jamboree Rd	1125-Traffic Hazard
10-27-20 08:07	225	99.5	I5 N - Jamboree Rd Ofr	1125-Traffic Hazard
10-27-20 08:53	109	88.8	I5 N - La Paz Rd	1125-Traffic Hazard
10-27-20 09:41	23	98.9	I5 N - CULVER DR	1125-Traffic Hazard
10-27-20 13:42	8	86.0	I5 N - Crown Valley Pkwy Cv	1182- Traffic Collision-No Inj
10-27-20 15:01	24	93.6	I5 N - I405	1125-Traffic Hazard
10-27-20 17:56	25	104.1	I5 N - Grand Av Onr	20002-Hit and Run No Injuries
10-27-20 18:00	15	104.1	I5 N - Grand Av Onr	20002-Hit and Run No Injuries
10-27-20 18:12	6	89.8	I5 N - Alicia Pkwy E Onr	1125-Traffic Hazard
10-27-20 18:11	7	89.8	I5 N - Alicia Pkwy E Onr	1125-Traffic Hazard
10-27-20 23:33	39	96.1	I5 N - Sand Canyon Av Ofr	1125-Traffic Hazard

10-26-20 06:55	13	90.9	I5 S - El Toro Rd	1182- Traffic Collision-No Inj
10-26-20 11:41	61	97.2	I5 S - JEFFREY RD	1125-Traffic Hazard
10-26-20 11:40	12	93.3	I5 S - I405 S	1125-Traffic Hazard
10-26-20 11:39	152	86	I5 S - Crown Valley Pkwy Cv	1182- Traffic Collision-No Inj
10-26-20 12:37	39	96.2	I5 S - Sand Canyon Ave	1125-Traffic Hazard
10-26-20 15:08	6	89.7	I5 S - Alicia Pkwy	1125-Traffic Hazard
10-26-20 21:07	56	86	I5 S - Crown Valley Pkwy Cv	-Assist with Construction
10-27-20 02:49	207	92	I5 S - Lake Forest Dr	CFIRE-Car Fire
10-27-20 06:33	12	104	I5 S - Grand Ave	1182- Traffic Collision-No Inj
10-27-20 06:31	37	104	I5 S - Grand Ave	1182- Traffic Collision-No Inj
10-27-20 08:15	12	98.8	I5 S - CULVER DR	1125-Traffic Hazard
10-27-20 09:46	12	98.8	I5 S - Culver Dr	1125-Traffic Hazard
10-27-20 09:44	13	98.8	I5 S - Culver Dr	1125-Traffic Hazard
10-27-20 11:33	8	88.7	I5 S - La Paz Rd Lp	1125-Traffic Hazard
10-27-20 11:39	12	88.7	I5 S - La Paz Rd Lp	1182- Traffic Collision-No Inj
10-27-20 13:04	48	90.9	I5 S - El Toro Rd	1125-Traffic Hazard
10-27-20 13:18	16	84.6	I5 S - Sr73	1183- Traffic Collision-Unknown Inj
10-27-20 13:40	37	90.9	I5 S - El Toro Rd	1125-Traffic Hazard
10-27-20 16:42	13	87.4	I5 S - Oso Pkwy	1183- Traffic Collision-Unknown Inj
10-27-20 17:55	11	100.1	I5 S - Jamboree Rd Ofr	1125-Traffic Hazard