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The Development of a Simple Engineering Calculation Method for Wildfire Evacuation Scenarios

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Abstract

Emergency planning is required to respond to the increasing wildfire threat. A part of this is to assess a community's capacity to move to a safe place during wildfires. This can be achieved by calculating the time it takes for a community to evacuate from an at-risk area to a relatively safe place. Simple approaches, such as the commonly used engineering calculation, may provide access to a broader group of practitioners to assess or estimate a community's evacuation time. However, currently there is no publicly available engineering calculation that considers community characteristics and road network for evacuation during wildfires. This work presents a first attempt to produce a simple set of engineering calculations to capture the impact of a wildfire emergency on traffic performance during an evacuation of a community. An existing mathematical traffic model, the Highway Capacity Manual (HCM) model, was identified and has been improved to represent traffic conditions during wildfire evacuations. Factors assumed to directly impact the traffic performance during evacuations were added to this model to improve the numerical framework representation of wildfire conditions and their impact on traffic movement. The factors were derived from conditions found in the past wildfire evacuations by reviewing previous wildfire evacuation case studies. The improved model was then applied and compared to an empirical data set from a past wildfire evacuation and showed a better representation than the existing theoretical model. A set of test cases was examined to investigate the impacts of the existing theoretical model improvements on predicted performance.

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Abstract

Emergency planning is required to respond to the increasing wildfire threat. A part of this is to assess a community's capacity to move to a safe place during wildfires. This can be achieved by calculating the time it takes for a community to evacuate from an at-risk area to a relatively safe place. Simple approaches, such as the commonly used engineering calculation, may provide access to a broader group of practitioners to assess or estimate a community's evacuation time. However, **currently there is no publicly available engineering calculation that considers community characteristics and road network for evacuation during wildfires.**

This work presents a **first attempt to produce a simple set of engineering calculations to capture the impact of a wildfire emergency on traffic performance during an evacuation of a community**. An existing mathematical traffic model, the Highway Capacity Manual (HCM), was identified and has been improved to represent traffic conditions during wildfire evacuations. Factors assumed to directly impact the traffic performance during evacuations were added to this model to improve the numerical framework representation of wildfire conditions and their impact on traffic movement. The factors were derived from conditions found in the past wildfire evacuations by reviewing previous wildfire evacuation case studies.

The improved model was then applied and compared to an empirical data set from a past wildfire evacuation and showed a better representation than the existing theoretical model. A set of test cases was examined to investigate the impacts of the existing theoretical model improvements on predicted performance.

Abstrak

Perencanaan darurat diperlukan untuk menanggapi dan merespon ancaman kebakaran hutan yang semakin meningkat. Salah satunya adalah dengan memperkirakan kemampuan masyarakat untuk melakukan evakuasi, yaitu proses perpindahan ke tempat yang aman saat terjadi kebakaran hutan. Hal ini dapat dilakukan dengan menghitung waktu yang dibutuhkan masyarakat untuk mengungsi dari daerah berisiko ke daerah pengungsian. Prosedur sederhana menggunakan perhitungan teknik dapat memberikan akses ke kelompok praktisi yang lebih luas untuk memperkirakan waktu yang dibutuhkan masyarakat untuk evakuasi. Namun, saat ini, tidak ada perhitungan teknik yang tersedia, yang dapat mempertimbangkan karakteristik masyarakat dan jaringan jalan untuk evakuasi selama kebakaran hutan.

Karya ilmiah ini menyajikan upaya pertama untuk menghasilkan satu set perhitungan teknik sederhana yang dapat merepresentasikan dampak dari kebakaran hutan pada kinerja lalu lintas saat masyarakat melakukan evakuasi. Di studi ini, pemodelan lalu lintas matematis yang sudah ada dimodifikasi agar dapat mewakili kondisi lalu lintas selama evakuasi kebakaran hutan. Faktor-faktor yang diasumsikan memiliki dampak langsung terhadap kinerja lalu lintas selama evakuasi ditambahkan ke kerangka numerik dari model yang ada. Faktor-faktor tersebut berasal dari kondisi yang ditemukan pada proses evakuasi kebakaran terdahulu, dengan cara meninjau studi tentang evakuasi kebakaran yang sudah terjadi.

Ketika dibandingkan dengan pemodelan lalu lintas yang sudah ada, model baru ini menunjukkan representasi yang lebih baik untuk satu kasus tersebut. Model baru ini menunjukkan representasi yang lebih baik untuk satu kasus tersebut, jika dibandingkan dengan pemodelan lalu lintas yang sudah ada. Serangkaian tes kemudian dilakukan untuk menyelidiki dampak model yang baru kepada waktu evakuasi masyarakat.

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I would like to express my immense gratitude to Prof. Steve Gwynne, who has been very encouraging and supportive throughout this project. Without his guidance, resources, and constructive feedback, I would not have been able to finish this thesis project. I would also like to thank Arthur Rohaert for his support—during our discussions and his valuable feedback while working on this project. I would like to thank Prof. Enrico Ronchi for supporting me with resources and guidance during my semester at Lund University and for reviewing this thesis to be made into its final form.

"A mind is not a vessel to be filled, but a fire to be kindled"—Plutarch

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List of Abbreviations

ASET	Available Safe Egress Time
AADT	Annual Average Daily Traffic
CAF	Capacity Adjustment Factor
ETE	Evacuation Time Estimates
FFS	Free-flow Speed
HCM	Highway Capacity Manual
LOS	Level of Service
PBD	Performance-based Design
PCE	Passenger car equivalent
RSET	Required Safe Egress Time
SAF	Speed Adjustment Factor
veh	Number of vehicles
WUI	Wildland-Urban Interface
WTEC	Wildfire Traffic Evacuation Calculation

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Terminology

Annual Average Daily Traffic: The average 24-hour traffic volume at a given location over a full 365 days per year

Background traffic: The existing traffic in the evacuation road network that is not a part of the active evacuation

Breakpoint: The threshold value where individual speed is affected by the number of vehicles present in the road segment

Capacity: The maximum number of vehicles that can use a road segment during a specific period

Clearance: The space between vehicles

Density: The number of vehicles on a given length of a lane at a particular instant

Flow: The number of vehicles passing a point during a time interval of less than one h but expressed as an equivalent hourly rate

Free-flow speed: The average speed of vehicles on a given segment when drivers are free to drive at their desired speed and are not constrained by the presence of other vehicles or downstream traffic control devices

Gap: The headway minus the total length of the vehicle

Headway: The time between the arrival of one vehicle at a particular location in the road segment and the arrival of the next vehicle at that same location

Jam density: The density when all vehicles stop

Macroscopic model: Model representing traffic in aggregate level and based on speed, flow, and density correlation

Mesoscopic model: Model representing the traffic entities at a high level of detail, but vehicles' behaviour and interactions are described at a lower level of detail

Microscopic model: Model describing traffic through the longitudinal (car-following) and lateral (lane-changing) behaviour of individual vehicles

Oversaturated flow: the conditions within a queue that has backed up from a downstream bottleneck. These flow conditions reflect the consequences of a downstream problem. All oversaturated flow is considered to be congested.

Spacing: The distance between the front of one vehicle and the front of the subsequent vehicle at a given point in time

Space mean speed: The average speed of all vehicles occupying a given section of a road over some specified time period

Speed: The rate of motion expressed as distance per unit of time

Time mean speed: The average speed of all vehicles passing a point on a road segment over some specified time period

Traffic assignment: The allocation of the evacuating vehicles to the available evacuation road networks

Travel demand: The number of vehicles desire to use a road segment during a specific period

Trip generation: The total number of trips generated by households in an evacuating zone

Undersaturated flow: The flow condition when the traffic streams are not affected by the upstream or downstream bottleneck

1. Introduction

1.1 Background

Wildfire risk is expanding and increasing given the environmental pressure from climate change (Abatzoglou et al., 2019; Dupuy et al., 2020; Jolly et al., 2015). This increase is also attributed to the rapid growth of wildland-urban interface (WUI) areas (Mockrin et al., 2022; Radeloff et al., 2018). Wildland-urban interface is defined as "an area where wildland interacts with urban areas, where the structures resulting from human development are located inside or in contact with natural vegetation" (Bento-Gonçalves & Vieira, 2020). Interaction between people, physical, and environmental elements in the WUI formed a highly coupled non-linear relationship that makes fire in the WUI areas more complex and harder to fight (Bento-Gonçalves & Vieira, 2020; Gaudet et al., 2020). In this context, the WUI community element includes demographics, proximity to wildland areas, community management, and their response to wildfires. The physical element includes road network availability, construction materials used in the built environment, and density between buildings. The environmental element consists of the local climate, topography, and types of fuels present. As WUI areas expand, the distance between communities and wildland vegetation becomes closer, exposing wildfire threats to more lives and properties, and human-induced ignition becomes more frequent (Nagy et al., 2018; Radeloff et al., 2018).

Destruction and loss of lives resulting from wildfires in recent years occurred in different regions across the globe, such as United States, Australia, Canada, Southern America, and in Mediterranean Europe (Butry et al., 2001; Cruz et al., 2012; Kramer et al., 2019; Oliveira & et. al., 2018; Papathoma-Köhle et al., 2022; Tymstra et al., 2020). Several recent wildfire events have demonstrated the significance of the problem faced across jurisdictions. For example, the 2009 Victoria bushfires, or also known as Black Saturday bushfires, is one of the most catastrophic bushfire disasters in Australia (2009 Victorian Bushfires Royal Commission, 2010). There were approximately 400 individual fires recorded on Saturday 7 February, and some lasted until February 14, resulting in a total of 173 fatalities, with more than 2000 homes destroyed, and approximately 7500 people were displaced. The 2016 Fort McMurray wildfire in Canada started on May 1 and spread across northern Alberta, and approximately burned 590,000 ha of land before it was declared under control on July 5, 2016 (Mamuji & Rozdilsky, 2019). This fire forced up to 88,000 people to evacuate from their homes, becoming one of the largest wildfire evacuations in Canadian history, with one of the problems being communities only having one road network to enter and leave their neighbourhoods. It was estimated that 2400 structures were destroyed, with some neighbourhoods declared as unsafe for re-occupation due to contamination from arsenic and heavy metals, including damages to its water system. The 2018 Camp Fire is one of the deadliest wildfires in California, affecting communities in Concow, Magalia, and Paradise in Northern California (Butte County District Attorney, 2020). The fire destroyed more than 19,000 structures, caused at least 85 fatalities, and evacuated 52,000 people their homes. Wildfire is therefore becoming a more severe problem and requiring community planning and response.

To conduct planning and manage response, community planners first need to assess a community's vulnerability. Vulnerability can be defined as community's characteristics (demographic and socioeconomic) that influence their capacity to prepare for, respond to, and recover from hazards (Cutter et al., 2003; Solangaarachchi et al., 2012). In the context of communities in the WUI, there are different elements that interact, and influences their vulnerability to wildfires. Due to the complex nature of WUI fire incidents, determining the area that might be exposed to WUI fires and understanding the wildfire development alone is not enough to assess their vulnerability – their response to wildfires needs to be understood (S. Gwynne et al., 2019).

Different frameworks and models have been developed to understand human response to wildfire incidents better. The most common protective action to wildfire is either stay (and defend in place), or evacuate to a place of relative safety (Folk et al., 2019; McCaffrey et al., 2020; McLennan et al., 2019). Evacuation is a strategy to leave an area at risk and reach a safe place. Therefore, communities' capacity to reach a place of safety should be assessed, which includes estimating their evacuation movement time.

A method is required to capture the different aspects (i.e., wildfire development, evacuation movement, etc.) of wildfires, that allows for making projection and assessing performance. Performance-based design (PBD) approach used in built environment fire safety engineering can be adapted to help authorities in assessing communities' level of safety (Kuligowski & Gwynne, 2021). This approach involves comparing the required safe egress time (RSET) (time it takes for population at risk to evacuate) with the available safe egress time (ASET) (the time until condition becomes untenable for population). However, the scale and longevity associated with wildfire evacuations present a different challenge with building fire evacuations (Ronchi et al., 2017). In building fires, evacuation movement is only formed from pedestrian movement, while in wildfires, vehicle movement needs to be taken into account – and is typically the main contributor to the time to reach safety given distances that need to be covered (Ronchi et al., 2017; Wahlqvist et al., 2021).

The method might examine wildfire development, pedestrian, and vehicle movement independently or in the same environment. Sophisticated models that combine two or more aspects in the same environment are currently available as a means of simulation, for example in work by Wahlqvist et al. (2021). Wildfire simulations can help establish how wildfires might develop and the areas that they might affect (i.e., spatiotemporal coverage), and evacuation simulation can provide projection on people's movement to reach a place of safety (i.e., their capacity to avoid the areas affected by the wildfire). It is also possible to obtain those results independently, without coupling the fire models with the pedestrian and traffic models. For example, in building fires PBD approach, engineers may examine fire development and spread through computational fluid dynamics simulation, obtain the ASET value, and compare it with result from evacuation models or engineering calculations (i.e., the RSET value) (Hurley & Rosenbaum, 2016).

Engineering calculations are available to obtain the result of time to evacuate all population in building fires, where evacuation is only formed by pedestrian movement (Gwynne & Rosenbaum, 2016). This method adopts basic hydraulic model to estimate evacuation time in a building fire. Such approach (an engineering calculation) may provide access to a broader group of practitioners, including those unfamiliar with computer simulations. It is making the concept of quantifying evacuation performance becomes accepted and commonplace. So far, however, **there is no publicly available engineering calculation that considers community characteristics and road network for wildfire evacuation scenarios.**

This work represents a first attempt to produce a simple set of engineering calculations to capture the impact of a wildfire emergency on traffic performance during an evacuation of a community.

1.2 Wildfire Evacuation Timeline

There are key differences that exist between wildfires and building fires. Work by Ronchi et al. (2017) identified the differences between wildfire and building fire scenarios. In fact, the difference was not only limited to evacuation mode (i.e., pedestrian or vehicle movement), but also the "spatial dynamism, temporal iterations, the range of influential factors and the multi-level organisational involvement" (Ronchi et al., 2017). These differences pose a unique challenge in designing possible evacuation timeline, that will enable for engineering calculation.

Lindell (2008) explained that the time for an individual or a household to evacuate after any incident initiation is a function of authority's decision time to send out evacuation order or notice, household's warning receipt time, household's evacuation preparation time, and household's evacuation travel time (Lindell, 2008). Ronchi et al

(2017) developed a provisional linear function that enables the calculation of a total evacuation time specifically for a wildfire evacuation. The timeline is shown as follows.

$$t_T = t_d + t_{FDA} + t_{FDI} + t_N + t_{prep} + t_{foot} + t_{veh} + t_{ref} \qquad \text{(Eq. 1)}$$

Where t_T is the time for the population to reach safety, t_d is the time for the incident to be detected after ignition, t_{FDA} is the time spent by the fire department assessing the situation on site, t_{FDI} is the time spent by the fire department intervening and attempting to control the incident, t_N is the time for the population to be notified once fire fighter intervention has been deemed unsuccessful, t_{prep} is the time for residents to complete preparations after they have initially been notified, t_{foot} is the time for the population to move to a target location on foot (e.g. to a vehicle), t_{veh} is the time for the population to move to a target location using a vehicle (e.g. to a refuge), and finally t_{ref} is the time for the individual to be on-boarded at a place of safety (e.g. enter a refuge centre).

Simplification was certainly involved in designing this timeline (Ronchi et al., 2017). Conditions will likely vary in different context (e.g., population and coverage size, geographical location, etc.), and the timeline may not always simply be linear. Nevertheless, this timeline provides an overview of stages in a wildfire evacuation scenario that might potentially have an impact, and thus can support in setting out the capabilities of the developed model in this study. As such, this study may focus on one of the time components from the total evacuation time.

From the total evacuation time, the time for the population to move to a target location using vehicles might be of planners' interest. Considering the spatial and temporal scale of a wildfire evacuation, the time for the population to move using vehicles takes up a substantial length of time until they arrive at a safe place.

1.3 Traffic Modelling

An evacuation model is defined as a qualitative (conceptual) or quantitative framework used to represent evacuee response, can be beneficial in assisting decision-making, and meant to improve people safety (Ronchi & Gwynne, 2020). Evacuation model as a tool can aid decision making in evacuation planning or during the response stage (i.e., real time application), as it may enable quantification of evacuation performance and the comparison of different evacuation scenario results. The practical use of evacuation models can aid authorities or planners to identify the "worst-case" scenario, and plan response (including evacuation) accordingly. When the evacuation is consisted of vehicle movement, traffic modelling is included as a part of the evacuation model. Vehicle-based evacuation modelling commonly considers four steps of modelling (Murray-Tuite & Wolshon, 2013), which are as follows.

- Trip generation
- Trip distribution
- Modal split
- Traffic assignment

Trip generation refers to estimating the number of trips generated from a population at risk (Murray-Tuite & Wolshon, 2013; Pel et al., 2012). To determine the number of the trips, there are two things that must be identified. The first is estimating the number of people who decide to evacuate from the total population. A range of factors can influence an individual or household decision to evacuate (Folk et al., 2019). Lovreglio et al. (Lovreglio et al., 2019) proposed a mathematical model on wildfire evacuation decision model that may be implemented in a wildfire simulation model to generate the number of people/household that will evacuate. The second is estimating the time evacuees leave. After authorities issue an evacuation order, people do not simultaneously respond to the order and leave their premises. There will be some preparation time, or even an intermediate trip, before evacuees leave. Research indicated that evacuees normally leave the risk area following different distributions (i.e., Poisson, Weibull, Rayleigh, or sigmoid), which is commonly formed as an S-shape curve (Pel et al., 2012).

Trip distribution predicts the number of trips between the origin (the area at risk) to the destinations (Murray-Tuite & Wolshon, 2013). In the context of wildfire evacuation, the destinations are related to the type of accommodations and its distance from the origin. People's destination choice affects the evacuation time calculation, as further destinations will result in longer evacuation times.

Modal split refers to estimating the proportion of trips in different transport modes (Murray-Tuite & Wolshon, 2013). Evidently, road vehicle is predominantly used during a wildfire evacuation (Wong et al., 2020). However, there were some instances where other transport modes were used (e.g., air transport (Woo et al., 2017)), or where pedestrian movement was significant (Toledo et al., 2018). The modal split may also pertain to the number of private vehicles used in a household, since evacuation decision is often assumed to be taken at a household level.

Finally, traffic assignment refers to allocation of the evacuating vehicles to the available evacuation road networks (Murray-Tuite & Wolshon, 2013). Given the destinations, evacuating vehicles are assigned to the available routes. In wildfire evacuations, people may tend to choose a route with the nearest exit from their starting point, and the shortest distance (Brachman et al., 2019). Findings from a hurricane evacuation study indicates that people tend to choose a familiar route (Lindell et al., 2011). The route choice affects the traffic volume in the evacuation routes. Driving parameters such as vehicles' speed and flow is included in the traffic assignment (Intini et al., 2019).

These four steps will eventually generate a travel demand, which is the number of people that desire to use a road or a road segment.

Different types and format of data needed at each step of the traffic modelling, and it depends on the modelling method (E. Kuligowski, 2021). Types of modelling methods are macroscopic, microscopic, and mesoscopic models (Intini et al., 2019). Macroscopic model means traffic is represented in aggregate level, it can predict broader traffic trends such as its capacity, flow, and average speed. In contrast, microscopic model can represent individual evacuating vehicles. Mesoscopic model lies between the two models.

Another important concept in the evacuation traffic modelling step is *shadow evacuation* and *background traffic* as these can affect the demand placed on the road network. Shadow evacuation is defined as movement of the evacuees that are not part of the mandatory evacuation (Murray-Tuite & Wolshon, 2013). This might refer to the residents at the risk area who evacuate before mandatory evacuation order was issued, or residents that did not receive the mandatory evacuation order but living in close proximity to the risk area. Background traffic refers to the (existing) traffic in the evacuation road network that are not a part of the active evacuation (Murray-Tuite & Wolshon, 2013).

1.4 Traffic Stream Characteristics

The traffic stream represented at a macroscopic level displays a broad traffic trend such as the traffic flow, density, and average speed. These are the variables of interest, measured over space and time, describing traffic stream performance (National Academies of Sciences & Transportation Research Board, 2016).

Flow (veh/hour) represents the number of vehicles passing a point at less than one hour but is expressed as an equivalent hourly rate. Density (veh/km) is the number of vehicles occupying a given length of a lane or roadway at a particular instant. Speed (km/h) is defined as a rate of motion expressed as distance per unit of time. There are two distinct ways to measure the average speed of a set of vehicles. The first way is by taking the arithmetic mean of the speed of observation, and this is called time mean speed (i.e., an average of observation taken over time). The second way is termed space mean speed, which is taken by measuring the average time taken by the vehicles to travel a given distance or space (i.e., an average of observations taken over space).

Work has been completed to determine the relationships between the variables described above, primarily using a mathematical model, with some based on empirical data. One of the basic concepts is the fundamental diagram. This diagram defines the relationship between two of the three main variables: average speed, flow, and density (Knoop & Daamen, 2017). It is important to note that most of the efforts to establish the fundamental diagram concern an uninterrupted flow condition. This flow condition refers to a “flow regulated by vehicle-vehicle interactions and interactions between vehicles and the roadway” (National Academies of Sciences & Transportation Research Board, 2016). An uninterrupted flow is found on a freeway or highway. Meanwhile, vehicles traveling through roads with intersection control are considered to be on an interrupted flow.

The fundamental diagram commonly employed the *space mean speed* in measuring the speed, which is an average observation taken over space. In this regard, the analysed space must have uniform characteristics along the width and length (National Academies of Sciences & Transportation Research Board, 2016). This requirement means that one analysis cannot include different road segment types (i.e., basic, merging, diverging, weaving). A basic freeway road segment cannot be analysed together with a merging segment (segment with an existing on-ramp). Therefore, to analyse a highway of a certain length, the analysis must be divided based on its segment type.

Once the fundamental diagram is established, traffic flow qualities can be determined across the road section being examined (Daganzo, 1997). From the analyses, one can obtain the road’s capacity, the maximum flow that can be maintained for a given time. Capacity determines the number of vehicles that can use a given road segment during a specific period (of the analysis). The corresponding density at this point is defined as the critical density. The critical density separates two regimes of flow: unsaturated (uncongested) and oversaturated (congested) regimes. In the undersaturated flow regime, the traffic stream is not affected by the upstream or downstream bottleneck (National Academies of Sciences & Transportation Research Board, 2016). Meanwhile, the oversaturated flow regime represents the condition within a queue because of a downstream bottleneck.

1.5 Evacuation Performance Measure

The capacity of the available road networks during a large-scale evacuation is of great importance in assuring robust evacuation operation, since the road network capacity and the evacuee’s mobility can be a measure of traffic performance during an evacuation (Menon et al., 2020). Different approaches are available to measure an evacuation performance that requires vehicle movement.

In the Highway Capacity Manual (HCM) released by the United States Transportation Research Board, a level of service (LoS) can be adopted as a measure of performance

(National Academies of Sciences & Transportation Research Board, 2016). The level of service can determine spacing between vehicles and at which speed, and flow rates vehicles are operating. Consequently, congestion experienced by the drivers can be examined through the LoS. To illustrate, Level of Service A assumes less than or equal to 11 vehicles per mile per lane, while Level of Service F is when demand exceeds 45 vehicles per mile per lane (LoS F is indicating a congested section). LoS as a performance measure allows for authorities or planners to determine the target LoS on an evacuation road network during a large-scale evacuation. An example of this measure was done in a non-emergency condition. For instance, Florida Department of Transportation issued a target of LoS C operation at the entire state highway for non-urbanised areas during peak hour traffic (non-emergency operations)(Florida Department of Transportation, 2017).

Another capacity-driven performance measure compares the travel demand with the road network capacity (Lindell et al., 2019). At aggregate level, an evacuation time estimate (ETE), which is the time to clear all populations from the danger area, can be obtained by simply dividing the evacuation demand (vehicles) by the evacuation route capacity (vehicles/hour). This condition is only applicable if congestion is ignored, but congestion is likely to happen during a mass evacuation. Nevertheless, this approach (of diving the evacuation demand by the route capacity) leads to general principles in managing large-scale evacuations. For a given available road network capacity, the ETE increases (i.e., longer travel time) if the evacuating population increases. For a given community size, the ETE decreases when available road network capacity increases. The ETE result may give evacuation planners insight in managing evacuation logistics, by managing travel demand and increasing road network capacity.

Dixit and Wolshon (2014) introduced a highway capacity measurement value derived from three hurricane evacuations empirical data. The study introduced two quantities: ‘’maximum evacuation flow rates’’ (MEFR) and ‘’maximum sustainable evacuation flow rates’’ (MSEFR). They suggested that these two quantities are the more accurate representation of capacity during a mass evacuation, since the suggested road capacity from the HCM (i.e., during non-emergency conditions) is higher than the empirical data. The implications of this finding for authorities or planners are: 1.) they may need to adjust their capacity to these values when using it as an assumption or input in simulations, and 2.) when estimating evacuation time. Rohaert et al. (2022) in their work examining wildfires evacuation traffic dynamics also found that theoretical capacity value is higher than one empirical data set during their study, based on traffic data from the 2019 Kincade wildfire(Rohaert et al., 2022).

1.6 Problem Statement

The increasing wildfire occurrence across the globe, and destructive effects from wildfires are causing safety concerns, especially to communities living close to or intermixing with wildlands. A method to assess the community's capacity to evacuate during wildfires is necessary to better prepare for wildfire hazards. Simple approaches such as engineering calculation may provide access to a broader group of practitioners for evacuation planning. These simple approaches will also be required to ensure that the concept of quantifying evacuation performance becomes accepted and commonplace. However, such a method currently does not exist for wildfire evacuation scenarios.

1.7 Project Aim and Objectives

The aim of this study is to develop a method to calculate evacuation time estimates for wildfire evacuation scenarios. The calculation will solely focus on estimating the time for a population to move to a target location using a vehicle. Time estimation will be derived from macroscopic model representing movement between leaving premises and reaching a safe place. The model will consider the current understanding of normal traffic flow, road network capacity, and factors that influence community response. This study will focus on developing the calculation for an uninterrupted flow (basic freeway or highway segment). It will inevitably be simpler than complete traffic movement analysis – but will provide a starting point for planning and assessment.

The following objectives are set out to reach the study goal.

- Identify factors that influence community response in wildfire evacuation scenario.
- Investigate the differences between normal and emergency traffic flow condition.
- Investigate the differences between normal and emergency road network capacity.
- Improve available engineering models to represent movement during wildfire evacuation scenarios. The developed model will be later referred to as Wildfire Traffic Evacuation Calculation (WTEC) model.
- Set out the time estimate calculation method that can be used by practitioners.

1.8 Scope

The project's scope is limited by the available engineering models that might be modified for application here and relevant traffic data that might support evacuation assessment. Therefore, data might be extracted from adjacent areas to inform the work conducted here (e.g., traffic movement during a hurricane evacuation).

The model will deliberately be simplistic to enable close scrutiny – especially for the test case selected. This is allowing for demonstration and comparison based on the evacuating populations with fewer confounding factors. It should therefore be considered very much a prototype – with lessons to be learned both from the developmental process and the prototype model produced.

2. Methodology

This study aims to develop a simple calculation of evacuation time during a wildfire scenario. As previously discussed, total evacuation time can be broken down into several stages. After the evacuating population is notified, they will take time to prepare for the evacuation, move to their vehicles, and then travel from the risk area to any refuge area through vehicles. This study focuses on developing a method to estimate the time vehicles take from the evacuating zone (area at risk) to a shelter or evacuation destination. A model that can describe the traffic performance of the evacuation route can be a means to estimate vehicles' travel time. However, previous studies suggested that traffic performance during a routine condition is different from an emergency condition (Dixit & Wolshon, 2014; Rohaert et al., 2022). Therefore, this study attempted to improve current traffic engineering modelling by reflecting the impact of wildland fire scenarios. The improved model will be referred to as the *WTEC Model*. In this section, the methodology to develop the WTEC model will be outlined.

The approach to inform and structure the development of such a model was as follows:

- Review publicly available traffic engineering models (Section 2.1), research reports on past wildfire evacuations (Section 2.2), and traffic performance during other emergency incidents (Section 2.3).
- Compile findings to identify improvements in the existing traffic model's numerical framework (Section 2.4)
- Compare the improved model (WTEC model) to an empirical data set from a past wildfire evacuation to check if the model improvement was going in the right direction to demonstrate traffic dynamics during a wildfire evacuation scenario (Section 2.5).
- A comparison between the base traffic model (i.e., traffic model describing traffic performance during routine) with the developed model was made by applying the two models to a set of test cases, allowing comparison, and establishing the method's credibility (Section 2.6).

The following sections describe in more detail each step of the process.

2.1 Traffic Models Review

Several publicly available traffic models were reviewed. The results produced are reported in Section 3.1. The review was meant to select an existing traffic model as the base model, and that would then be further enhanced to reflect wildfire evacuation scenarios. Therefore, the review focused on the deterministic mathematical models that can describe traffic flow conditions on a macroscopic scale. This approach has been adopted because in the macroscopic model, the links between traffic flow, density, capacity and average speed are expressed in an aggregate manner (Intini et al., 2019). Additional advantages of using models at the macroscopic level are it allows for a relatively quick assessment, and capacity reduction due to conditions during the wildfire evacuation can be explicitly modelled (Intini et al., 2019).

The United States Transport Research Board published a Highway Capacity Manual (HCM) containing concepts, guidelines, and computational steps for computing the capacity and quality of service in various highway facilities (National Academies of Sciences & Transportation Research Board, 2016).

Traffic analysis using HCM allows for analysis with a high level of scope considering a number of different factors that may affect the results produced. HCM provides methodologies for estimating and predicting performance measures for specific highway facilities. For instance, HCM contains specific calculation procedures for different highway segments (i.e., basic, weaving, merge, and diverge segments) (National Academies of Sciences & Transportation Research Board, 2016). Due to HCM's detailed description of its methodology, HCM allows for reproducibility and comparison. Although published by the United States Transport Research Board, methodologies outlined in HCM are also used in traffic engineering studies in other regions (Mohajeri & Akbarzadeh, 2020; Pompigna & Rupi, 2015). HCM is frequently updated to incorporate the latest findings from traffic-related studies research. Given this, the HCM model is chosen as the base model in this study. The 6th Edition of the Highway Capacity Manual (National Academies of Sciences & Transportation Research Board, 2016) is used as the reference for this study.

2.2 Review of Past Wildfire Evacuation Studies

A review of research reporting past wildfire evacuation incidents has been conducted. The results of this review are reported in Section 3.1. The research reporting wildfire incidents requiring vehicle evacuation were chosen as the primary sources. The review was carried out to establish a qualitative understanding of the past wildfire evacuations, primarily on the attributes that may affect traffic flow during such conditions. These attributes might then be considered for inclusion in the engineering calculations proposed here. A database of large outdoor fires requiring evacuation (Ronchi et al., 2021) was selected as the reference point to look up the case studies. Further search for each case was carried out using Google Scholar with additional keywords such as "WUI Fire", "wildfire", "evacuation", "traffic", "traffic dynamics", and "traffic performance". The major drawback of this method is that Google Scholar may show materials that are not peer-reviewed. However, peer-reviewed materials were chosen as the primary sources in this case. When there is a little to no data exist, other materials were used as a supplement.

There was only a limited number of research reporting vehicle evacuation during a wildfire incident. Although wildfire incidents occurred in many regions of the world, reports describing wildfire evacuations were mainly from the US. It is because of the extent and frequency of wildfire in the region. Such limitation means that the improved model may not capture all phenomena occurring in a wildfire evacuation scenario. Especially since wildfire evacuation is location-specific, and location-specific characteristics are possibly not embodied in the developed model. However, the developed model attempted to represent key factors identified in most wildfire evacuation cases.

2.3 Hurricane Evacuation Studies Review

Studies describing traffic performance during past evacuations in other disasters were reviewed. The review focuses on hurricane disasters to gather more data on evacuation traffic dynamics where little to no wildfire data exist. Due to the time constraint of this project, the review was only conducted on hurricane disasters given this category of material was most prevalent. Most importantly, traffic movement during hurricane events is a more mature area of research and therefore produces a larger body of material. A search was conducted on Google Scholar using keywords such as “evacuation”,” emergency”, “traffic dynamics”, “traffic performance”, “model”, and “hurricane”.

There are concerns regarding the applicability of findings from hurricane research to wildfire evacuation scenarios (Kuligowski, 2021). It is due to the difference between wildfire and hurricane scenarios, such as longer warning times for hurricanes than wildfire (Lindell et al., 2019). Areas at risk from a hurricane can be predicted more accurately than areas at risk from wildfires (E. Kuligowski, 2021). A phased evacuation strategy is more often employed as a hurricane evacuation strategy (Lindell et al., 2019). Meanwhile, due to wildfires’ rapid and unpredictable development, authorities often fail to implement phased evacuation (Folk et al., 2019). Phased evacuation is the systematic removal of people from the area at risk starting from the most dangerous area.

2.4 HCM Model Improvement

Findings from the previous literature review were compiled, and the HCM model’s numerical framework was improved based on these findings to reflect wildfires evacuation conditions. The model improvement will be referred to as the *WTEC model* to avoid confusion. The base speed-flow-density curve was created following HCM methodology using Microsoft Excel.

HCM uses a passenger car equivalent (PCE) as the basis of its calculation (National Academies of Sciences & Transportation Research Board, 2016). Hence, when heavy vehicles are present in the analysed segment, the analyst should convert them to a passenger car equivalent. This conversion requires detailed information on the share of different vehicle types (percentage of heavy vehicles, proportion of single-user truck and truck trailer), terrain conditions, and traffic conditions at peak hour. Since this detailed information might be missing for simple analysis, the mixed vehicle approach will be chosen. An additional publication by the United States Transportation Research Board (Dowling et al., 2016) suggested a reduction of capacity to 80% from passenger cars equivalent (pce) to number of mixed vehicles (veh). This conversion will be applied to all the methodology of HCM so the units used in this study will be in a mixed-vehicles (veh) form.

Some of the key attributes found in wildfire evacuations were assumed to impact the traffic flow's main parameter (i.e., capacity, speed, and density). These attributes were identified from the Review of Past Wildfire Evacuation Studies (Section 2.2) and Hurricane Evacuation Studies Review (Section 2.3). The impacts of these attributes to the traffic flow parameters were grouped as an assumption. For example, towing additional items and driving through smoke may increase the gaps between vehicles and thus reduce the capacity. Therefore, given these two attributes, a reduction of capacity was assumed for the model, and the impact of such reduction will be shown in the result Section 3.4. There are also other assumptions made based on the key attributes found in wildfire evacuations.

The assumptions directly impact the speed-flow-density diagram that describes the traffic performance of the analysed system. It changes the speed-flow-density diagram relationship curves generated based on the methodology in HCM model. The WTEC model was established by modifying the speed-flow-density curves' shape to better reflect conditions found in wildfires.

In HCM, capacity and speed reduction can be explicitly expressed using the Capacity Adjustment Factor (CAF) and Speed Adjustment Factor (SAF) (National Academies of Sciences & Transportation Research Board, 2016). These factors are incorporated in the original HCM numerical framework to reflect an adverse weather effect that may reduce the maximum achievable capacity, such as a snowy road or a foggy environment. To illustrate, when there is no capacity reduction, then the CAF value will be 1.0, and when there is a 10% capacity reduction, the CAF value employed is 0.9. The assumptions are incorporated into the WTEC model through these coefficients.

The assumptions and how each assumption modify the speed-flow-density curves are presented in Section 3.4.

2.5 Comparison with Empirical Data

An empirical data set from a past wildfire case was identified and then compared with the developed model (WTEC model) – i.e., formed a benchmark against which the WTEC model predictions might be compared. Work by Rohaert et al. (Rohaert et al., 2022) developed the speed-flow-density relationship curves from 2019 Kincade Fire data and fitted the data to a theoretical curve following Daganzo's (1994) model. The derived curve representing real-world evacuation performance was compared with the WTEC model curve to enhance the credibility and confidence of the WTEC model. In the 2019 Kincade Fire case, there were five highways that served as the primary evacuation routes. US101 highway was chosen as the main site of the study by Rohaert et al. (2022).

Traffic stream analysis using HCM methodology demands the analyst to select a segment in a highway. A highway can consist of a set of basic segments, weaving segments, and merging or diverging segments. A weaving segment is formed when merging segment closely followed by diverging segment, hence it is defined as the crossing of two or more traffic flow traveling in the same direction along a certain length of highway (National Academies of Sciences & Transportation Research Board, 2016). The analysis of these segments requires distinct methodology outlined in the HCM. For a highway with a specific length, the analyst begins with dividing the highway based on the segment type and the analysis is done in each segment.

2.6 Testing The Model

The WTEC model curve and the original HCM curve are applied to a set of test cases. It was performed to see if using HCM model and the WTEC model curve give different evacuation time estimates (i.e., to establish what the impact of applying a generic traffic model to wildfire evacuation scenarios might be and, by implication, what the benefit of the WTEC model development might be). Additionally, the tests were done to assess the difference and gain insights from the result provided by the two curves. To create the test cases, a verification and validation study of a WUI Fire model, WUI-NITY model, (Ronchi et al., 2022) was used as the reference guideline. The test case will be oversimplified from the reality to gain insights on the basic factors that were being assessed.

2.6.1 Basic Configuration

The test case employed a hypothetical community with the following characteristics and assumptions. As the base model used to develop a traffic evacuation calculation model in this study is based on the data and studies taken from the United States, the test case's population and geometry also reference data from the United States. This choice limits the applicability of the WTEC model. This provides a degree of consistency between the base method and the case explored that is useful for this demonstration case.

Population

- Total population: 26000 people. The population of Paradise town in California in the 2018 Camp Fire incident is taken as the reference (*U.S. Census Bureau QuickFacts*, 2018).
- All evacuees are assumed to respond to the evacuation order (100% response).
- People per household ratio: 2.57 people/household. This value is chosen since it is the average ratio in the United States (*U.S. Census Bureau QuickFacts*, n.d.).
- The evacuation decision is assumed to be at the household level.
- Vehicles per household ratio: 1.38 veh/household. This value is chosen based on previous studies during hurricane evacuations (Lindell et al., 2019). This ratio means that each household carries more than one vehicle during evacuation.
- The conversion from total population to the total number of vehicles evacuating is based on equations 7.2 – 7.3 in Lindell et al. (2021) as shown in Equation 2.

$$EV_R^z = \frac{E_R^z}{PHH_R^z} \times VHH_R^z \qquad \text{(Eq. 2)}$$

Where EV_R^z is the number of evacuating residential vehicles from zone z. E_R^z is the number of evacuating residents from zone z. PHH_R^z is the number of persons per households for zone z. VHH_R^z is the number of vehicles used per household for zone z.

Geometry

- The geometry of the evacuating zone, refuge zones, and evacuation routes is shown in Figure 1.
- Number of evacuation routes: 4. Each evacuation route corresponds to one evacuation zone (Figure 1). Meanwhile, in a real-life situation, it is possible that an evacuation route is used by different evacuees having different destinations. This road network is a simplified road network which limits the route choice modelling employed in the test cases (deliberately allowing us to focus on the application of the model on a simple situation).
- Evacuation routes length are as follows.
  - Route A: 5 km

  - Route B: 15 km
  - Route C: 25 km
  - Route D: 35 km.
- All road network has a speed limit of 120 km/h. This speed limit is chosen arbitrarily since the standard speed limit in the US highway is between 80 km/h to 120 km/h (National Academies of Sciences & Transportation Research Board, 2016).
- Total number of lanes: 4.
  - Lanes going out of the evacuating zone: 2.
  - Lanes going into the evacuating zone: 2.
- Road section characteristics are as follows.
  - Ramp density : 0 ramps/km
  - Lane width : 3.7 m
  - Lateral clearance : 1.8 m
  - The segment is a basic freeway segment (no on- or off-ramps in the middle of the segment, no weaving segment), and conditions (in terms of road type, width, environmental conditions, and terrain) are consistent along the segment.
- The geometry is a deliberate oversimplification, since a road segment may actually consist of on-ramps, off-ramps, or a weaving segment. The only difference between the four road networks' characteristics is the road length. This oversimplification ensures consistency in the analysis along the road section, so that one methodology (i.e., basic freeway segment methodology) can be used as a focus and allow a simple assessment of the model's effectiveness to be examined at this early stage of development.
- Road network C is arbitrarily chosen as the primary road network analysed here.
- Background traffic is the additional traffic on the road by non-evacuation trips. In all analyses, the background traffic is assumed to be 0 veh/km/lane, allowing the comparison of the two models (HCM and WTEC) to be purely based on the evacuating populations with fewer confounding factors – so that the impact of changes in the fundamental diagrams can be focused upon.
- The time when the evacuating vehicles leave their houses, travelling through arterial roads inside the evacuating zone until they enter the evacuation road network, is assumed to be negligible. This assumption was made for simplification since the test case was meant to serve high-level analysis on the primary evacuation route.

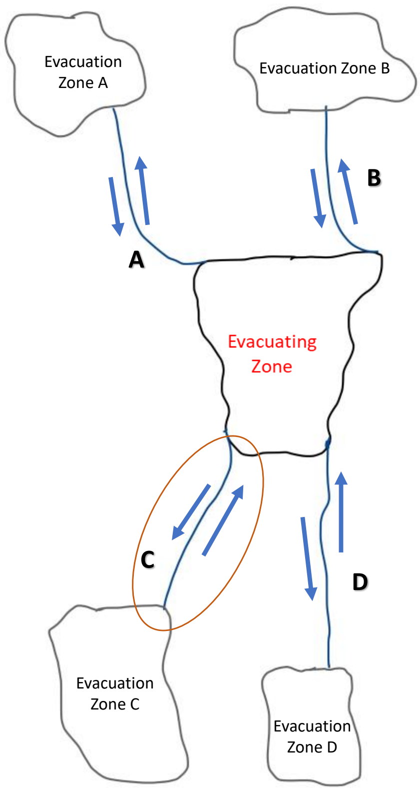


Figure 1. Road network of the evacuating zone

2.6.2 Scenario Generation

The scenarios examined are generated based on several modelled factors: the departure time, route choice, lane reversal operation, and smoke presence. These parameters are relevant to the wildfire evacuation scenario since some varying conditions of those parameters were observed in previous wildfire evacuation events (Wong et al., 2020).

- *Departure time*

Firstly, the departure time is defined as the time from evacuees receiving an evacuation order to the point when they start moving. In the scenario, it will be set to either 0s departure time or following a Rayleigh distribution (Woo et al., 2017). When the departure time is set to 0s, all evacuating vehicles enter the evacuation route at the same time. It means that all evacuees are ready to enter the route and are only constrained by the road capacity. The scenarios that follow 0s departure time are Scenario 1-8. This scenario, although unrealistic, places *maximum* emphasis on the differences in the modelled movement assumptions.

In reality, there will be different departure times between households as households might have different preparation times and possibly an intermediate trip, which is a trip to gather family members (Folk et al., 2019; Toledo et al., 2018). Previous research indicated that evacuees respond following different distributions (i.e., Poisson, Weibull, Rayleigh, or sigmoid), which is commonly formed as an S-shape curve, to show the percentage of departures in each time interval (Murray-Tuite & Wolshon, 2013; Pel et al., 2012; Woo et al., 2017). A cumulative Rayleigh distribution is used in the scenario to model the percentage of evacuees departing into the evacuation route in hourly time intervals. Rayleigh distribution is chosen as evacuation response since it has a shorter tail of an S-shape curve, which means that evacuees respond quickly after an evacuation order was issued (Lindell et al., 2019).

In other scenarios, it will be assumed that all evacuees respond within 20 hours after the evacuation order was issued. The scenarios that follow this assumption are Scenario 9-16. This assumption is based on previous studies that show that response time in wildfire events is faster than in hurricane disasters (E. Kuligowski, 2021). Hence the response time of less than 24 hours is taken as a scenario. Figure 2 shows an example of a cumulative number of vehicles entering the evacuation route (Evacuation Route C, with 25% of total evacuating vehicles). This is selected simply as a representative indication of what such delay distributions might be, rather than an attempt to reflect expected delays at this particular location and modelled population – to broadly represent the envelope of conditions where maximum demand is placed on the road network capacity to when this demand is a distribution over an extended period of time.

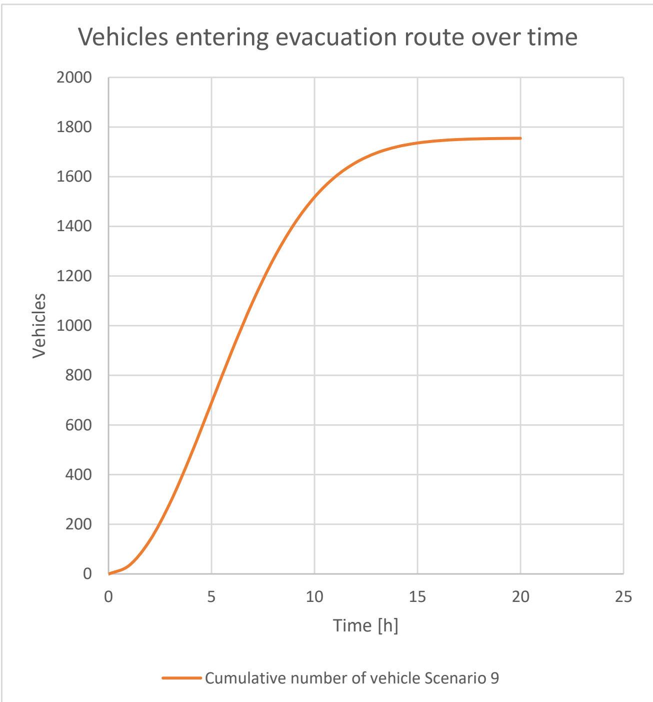


Figure 2. Cumulative number of vehicles entering evacuation route following Rayleigh distribution

- *Route choice*

The second parameter examined is route choice. Route choice impacts the number of vehicles that desire to use a particular route (producing traffic demand along that route). However, in reality, an evacuation route may be lost due to wildfire, blocked by debris, or in some cases, closed for the emergency responders to enter the evacuating zone and do a firefighting operation (i.e., as part of traffic management) (Wong et al., 2020). When this happens, a route is occupied by more vehicles than the routine or initial condition. To see the impact of a route loss, the basic scenario uses an even distribution across all 4 evacuation routes, and in other scenarios (Scenarios 5-8, and Scenarios 13-16), one route is occupied by more vehicles due to a route loss. In the basic scenario, Route C will be occupied by 25% of the evacuating vehicles. In the route loss scenarios, Route B is blocked, so that Route C will be occupied by 50% of the evacuating vehicles. It is important to note that the test cases employed a static route choice, which means the test cases are not accounting people changing their route choice due to evolving condition as the incident progresses. In reality, such situations may likely evolve over time. However, the intention here was to explore divergence between HCM and WTEC predictions; static conditions supported and simplified this comparison.

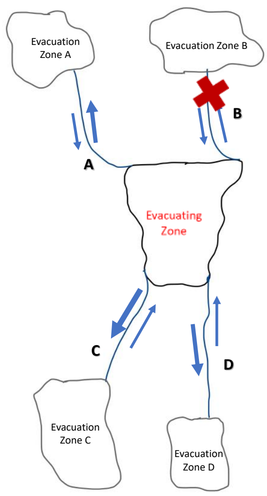


Figure 3. Illustration of a roadblock in Route B

- *Lane reversal operation*

The third parameter is the lane reversal operation – an approach employed to manage the capacity of routes in/around an evacuating community (Lindell et al., 2019). Lane reversal or contraflow operation impacts the number of vehicles that can use a route (traffic capacity) without directly changing the speed-flow-density relationship curves' shape. Such an operation was introduced in wildfire and evacuation scenarios to ease bottlenecks by adding more lanes in a direction out of the evacuating zone. In scenarios with lane reversal operation, the number of lanes in Route C was added so it had three lanes.

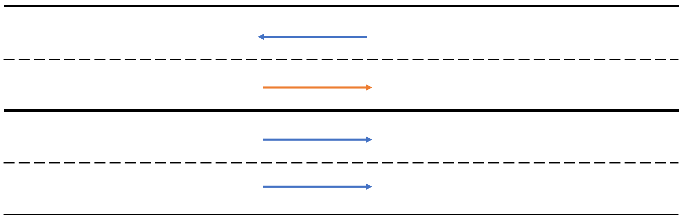


Figure 4. Lane reversal illustration of Route C

- *Smoke presence*

The last parameter is the smoke presence. The presence of smoke on the road segment is assumed to reduce the average speed (given reduced visibility) and increase vehicles' headway (Hoogendoorn et al., 2010; Wetterberg et al., 2021) (given perceived consequences of a road accident leading to attempt to minimise probability of such incidents). To see the impact of driving through smoke, the scenarios was generated with and without smoke presence.

The scenarios were generated based on the parameters highlighted above. Table 1 indicates all the scenarios.

Table 1. Test case scenario

Departure Time	***Route Choice***	***Lane reversal***	***Smoke presence***	***Scenario***
Leaving at the same time	Distributed evenly (25% of total vehicle on each evacuation route)	No	No	1
			Yes	2
		Yes	No	3
			Yes	4
	1 Route loss (Route A: 25%; Route C:50%; Route D: 25%)	No	No	5
			Yes	6
		Yes	No	7
			Yes	8
Rayleigh distribution	Distributed evenly (25% of total vehicle on each evacuation route)	No	No	9
			Yes	10
		Yes	No	11
			Yes	12
	1 Route loss (Route A: 25%; Route C:50%; Route D: 25%)	No	No	13
			Yes	14
		Yes	No	15
			Yes	16

Based on the parameter settings in each scenario, the HCM and WTEC model curve can be established and used as the tool to calculate evacuation time estimates.

2.6.3 Evacuation Time Estimates

The approach employed to generate evacuation travel time estimates will be based on Section 6 (Chapter 25) of the Highway Capacity Manual 6th Edition (National Academies of Sciences & Transportation Research Board, 2016). Some modifications were required due to the conversion of passenger car equivalent (pce) to a mixed vehicle (veh) value employed in WTEC model (modifications are noted in the description below). The steps to calculate will be presented in the following sections.

Step 1. Determining demand flow

Evacuation hourly demand is determined following the departure time of the evacuees. In Scenarios 1-8, all evacuees attempted to enter the evacuation route at the same time, so the demand is the total number of vehicles at Route C. In these scenarios, the vehicles were ready to enter at time zero and were only limited from doing so by the route capacity. Meanwhile, the inflow (hourly) will be different in Scenarios 9-16. It follows the Rayleigh distribution as explained in the previous section.

Demand at section i at time t is calculated by

$$d_{i,t} = d_{i-1,t} + \left(q_{i,t}\right)_{in} - \left(q_{i,t}\right)_{out} + d'_{i,t-1} \qquad \text{(Eq. 3)}$$

Where $d_{i-1,t}$ is the demand at the previous section, $\left(q_{i,t}\right)_{in}$ is the inflow at section i during analysis period t, $\left(q_{i,t}\right)_{out}$ is the outflow at section i during analysis period t, and $d'_{i,t-1}$ is the carryover demand from the previous analysis period (in the case of oversaturated condition).

The carryover demand is also an indication of a queue in section i. The queue in this case only stacked vertically and does not spill back upstream. The carryover demand is calculated as follows.

$$d'_{i,t-1} = Max\ (\ d_{i,t} - c_i, 0) \qquad \text{(Eq. 4)}$$

Where c_i is the capacity of section i.

Step 2. Determining capacity

The capacity is derived from the model speed-flow curve. After the HCM and WTEC model curves are established based on the scenarios, the capacity can be obtained from these model curves. It is important to note that the scenarios with and without smoke present assumed to generate different WTEC Model curves.

Step 3: Calculation of delay rate estimation

The delay rate (h/km or min/m) is estimated by obtaining the travel time difference between the free flow and the actual conditions and dividing it by segment length. For example, if a space mean speed of road section is 50 km/h relative to a free-flow speed of 75 km/h for a 0.5-km segment, then the free-flow travel time is 0.4 min, and the actual travel time is 0.6 min. The delay rate per kilometre is the difference between those travel times divided by the segment length, which gives a delay rate of 0.4 min/km. The delay rate calculation depends on the conditions of the flow (undersaturated or oversaturated). The demand to capacity ratio of more than one indicates that the traffic flow is oversaturated, and there might be a queue length.

When the demand over capacity ratio (d/c) is equal to or less than one, the traffic flow is considered to be *undersaturated*. For the undersaturated condition, the basic freeway segment speed–flow curve (from HCM and WTEC model) can be used to estimate delay rates. The delay rate under an undersaturated flow condition is calculated as follows.

$$\Delta_{RU_{i,t}} = \left(\frac{L_i}{S_{i,t}} - \frac{L_i}{FFS}\right) \times \frac{1}{L_i} \qquad \text{(Eq. 5)}$$

Where L_i denotes the segment length. $S_{i,t}$ denotes the speed of segment i at corresponding to the demand flow at time t, which can be obtained from the model speed-flow curve. FFS denotes the free-flow speed in section i according to the corresponding speed-flow curve.

When demand over capacity ratio (d/c) is more than one, the flow is in *oversaturated condition*. For oversaturated condition, the additional delay rate is approximated assuming uniform arrival and departures at the bottleneck location, which is calculated as follows.

$$\Delta_{RO_{i,t}} = \frac{D_c \times 10}{L} \times Max\left(\frac{d_{i,t}}{c_i} - 1,0\right) \qquad \text{(Eq. 6)}$$

Where $d_{i,t}$ is the demand flow of segment i at time t, and c_i is the capacity of segment i. D_c is density at capacity. It is important to note that the original equation from HCM denotes density at capacity as 45 passenger car/mi/lane (=22 veh/km/ln). Given that the calculation in the WTEC model converted passenger car value with mixed vehicle value (veh), so the density at capacity employed here is 22 veh/km/ln. An alteration of the formula was made into Equation 5, so it can use a consistent density-at-capacity (D_c) value.

Additionally, when demand exceeds capacity, any demand that cannot pass through the bottleneck is stored upstream of the bottleneck in a queue. Estimation of the queue length will be explained in the later step.

Step 4: Average travel time calculation

After the delay rate is determined, the travel rate is computed by summing the delay rate and travel rate under free-flow conditions, as shown below.

$$TR_{i,t} = \Delta_{RU_{i,t}} + \Delta_{RO_{i,t}} + TR_{FFS} \qquad \text{(Eq. 7)}$$

Where $TR_{i,t}$ is the travel rate on segment i in analysis period t (min/m), TR_{FFS} is the travel rate under free-flow conditions (min/m), and all other parameters are as previously defined. The travel rate under free-flow conditions is just the inverse of the free-flow speed. Finally, the section travel time ($T_{i,t}$) is then computed by multiplying the travel rate and segment length, as shown below.

$$T_{i,t} = TR_{i,t} \times L_i \qquad \text{(Eq. 8)}$$

The average speed can be calculated by dividing the segment length with the average travel time. The density is calculated by dividing the demand of vehicles by the average speed.

$$D = MIN(\frac{d_{i,t}}{S_{i,t}}, Djam) \qquad \text{(Eq. 9)}$$

From the density, the queue length can be estimated by dividing the difference in lane demand and capacity (demand that cannot be served by the road capacity) by density.

2.6.4 Result Presentation

All evacuation time estimate calculations were completed using Microsoft Excel. The test case results are presented using the format outlined in Table 2. For completeness, these are the results reported for each scenario, although the focus of the discussion will vary depending on the nature of the results.

Table 2. Result presentation for the test cases

Variables	***Units***	***Description***
Entrance flow	[veh/h/ln]	The flow entering the analysed road section at time t
Exit Flow	[veh/h/ln]	The flow exiting the analysed road section at time t-1
Carryover demand	[veh/h/ln]	The demand that was not served by the analysed road section from time t-1
Demand	[veh/h/ln]	Total vehicles that desire to use the analysed road section
Capacity	[veh/h/ln]	Total vehicles that can use the analysed road section
d/c	[-]	Demand over capacity ratio
ΔUR	[min/km]	Delay rate in an undersaturated flow
ΔOR	[min/km]	Delay rate in an oversaturated flow
TR_{FFS}	[min/km]	Travel rate in free flow speed condition
TR	[min/km]	Average travel rate

Variables	***Units***	***Description***
T_{avg}	[min]	Average travel time
S_{avg}	[km/h]	Average speed
D	[veh/km/ln]	Density
d-c	[veh]	Demand minus the capacity at time t
queue length	[km]	Total queue length

3. Results

The result from the study will be outlined in this section

- A summary from traffic model review is presented in Section 3.1.
- A summary on the Highway Capacity Manual model is explained in Section 3.1, including the methodology to construct a speed-flow-density relationship diagram.
- A summary of findings from wildfires report will be outlined in Section 3.3.
- The model improvement to construct the WTEC model is presented in section 3.4. This section includes the explanation of the logic and the assumptions that the WTEC model is based on.
- Section 3.5 presents the comparison between the HCM and WTEC models with the 2019 Kincade fire case study (Rohaert et al., 2022).
- Finally, the result from the test case is presented Section 3.6.

3.1 Existing Traffic Model

The traffic models being reviewed are models describing traffic flow at a macroscopic level. At macroscopic level, traffic flow can be describe using the fundamental diagram (or a version of it). The diagram defines the relationship between two of the three main variables: average speed, flow, and density. Once a fundamental diagram is established, one can assess traffic flow qualities in an analysed section of road. From the diagram one can obtain the road section's capacity, which is the maximum flow that can be maintained for a short time (specified by the method or the user). The time period is specified by the user, depending on the time interval taken during the flow measurement in the field. The period is normally less than an hour. Capacity determines the number of vehicles that can use a given road section during that specific period. The corresponding density at this point is defined as the critical density. The critical density separates two regimes of flow: unsaturated (uncongested) and oversaturated (congested) regimes. In the undersaturated flow regime, the traffic stream is not affected by the upstream or downstream bottleneck. Meanwhile, the oversaturated flow regime represents the condition within a queue because of a downstream bottleneck.

Greenshields (Greenshields, 1934) was the first to observe traffic flows and theorised a linear relationship between speed and density. The relationship between speed and density corresponds to a parabolic relation between speed and flow, as indicated in Equation 10.

$$v = v_f \left(1 - \frac{k}{k_j}\right) \qquad \text{(Eq. 10)}$$

v (km/h) indicates speed (km/h), while k (veh/km/lane) is the current density. v_f (km/h) indicates a free-flow speed, which is the average speed of vehicles on a given segment when drivers are free to drive at their desired speed and are not constrained by other vehicles or downstream traffic control devices. k_j (veh/km/lane), indicates the density when there is no movement which is called the jam density. Both the undersaturated and oversaturated flow are described using the same formula. This is why the Greenshields fundamental diagram is called a univariate model (Knoop & Daamen, 2017).

Drake's model (Drake et al., 1965) is also a univariate model, where the speed is described as an exponentially decreasing function of the density. Drake's model is described in Equation 11 below.

$$v = v_f e^{\left(-\frac{1}{2}\left(\frac{k}{k_c}\right)^2\right)} \qquad \text{(Eq. 11)}$$

k (veh/km/lane) indicates the current density, while k_c (veh/km/lane) indicates the density at maximum capacity. v_f indicates a free-flow speed. When two different formulas are used to describe the undersaturated and oversaturated regime, it is called a two-variate model (Knoop & Daamen, 2017). An example of this model is the truncated triangular fundamental diagram by Daganzo (Daganzo, 1997). It is described in equation 12.

$$v = \begin{cases} v_f, & 0 \leq k \leq k_c \\ q_c\left(\frac{1}{k} - \frac{1}{k_j}\right), & k_c \leq k \leq k_j \end{cases} \qquad \text{(Eq. 12)}$$

q_c(veh/h/lane) indicates the maximum flow, which is the flow at maximum capacity. v_f (km/h/) indicates a free-flow speed. k (veh/km/lane) is the current density, and k_j (veh/km/lane) indicates the jam density.

Meanwhile, Edie (Edie, 1961) fitted fundamental diagrams curves from Chicago highways data and separated the undersaturated and oversaturated regimes. In his model, the undersaturated regime has a maximum flow at the capacity, while the oversaturated regime has a different maximum flow called the queue discharge rate. The maximum flow capacity is higher than the queue discharge rate, and the curve is discontinued between the undersaturated and oversaturated regimes.

3.2 Highway Capacity Manual

United States Transport Research Board published a Highway Capacity Manual (HCM) containing concepts, guidelines, and computational steps for computing the capacity and quality of service in various highway facilities (National Academies of Sciences &

Transportation Research Board, 2016). The HCM is primarily set up for traffic analysis in normal conditions with associated scenarios.

In the HCM, the speed-flow-density relationship is described differently in two traffic flow conditions: undersaturated and oversaturated flow.

3.2.1 Undersaturated Flow in HCM

In the undersaturated flow regime, the traffic stream is not affected by the upstream or downstream bottleneck (National Academies of Sciences & Transportation Research Board, 2016). Traffic operation under an undersaturated condition is described in the following form.

- Speed is a constant in a range of flow rates (vehicle/hour). The flow rate range extends from zero to a breakpoint value.
- Breakpoint value (veh/hour) is a threshold value where individual speed is affected by the number of vehicles present in the road segment. From zero flow until breakpoint is reached, individual vehicle can maintain its desired speed and not constrained by the number of vehicles in the segment, which is called as the free-flow speed. From breakpoint to capacity, the speed decreases from the free flow speed in a parabolic relationship.
- In all cases, the capacity is defined when stream density is 45 pc/mi/lane (=22 veh/km/ln).

The following is the HCM methodology to formulate the speed, flow, and density relationship diagram under unsaturated flow condition. The methodology is outlined in Chapter 12 of the Highway Capacity Manual 6th Edition (National Academies of Sciences & Transportation Research Board, 2016). Note that this methodology is strictly use for a basic freeway segment. This methodology will be used throughout this study to generate the traffic fundamental diagrams, as it will be applied to the evacuation time equations.

1. Estimate the Free Flow Speed (*FFS*). It is calculated with Equation 13.

$$FFS = BFFS - f_{LW} - f_{LRC} - 3.22 \times TRD^{0.84} \qquad \text{(Eq. 13)}$$

Where FFS is the free-flow speed of the basic freeway segment (km/h). $BFFS$ is the base speed limit for the basic freeway segment (km/h). f_{LW} is the adjustment for lane width (km/h). f_{LRC} is the adjustment for lateral clearance (km/h). TRD is the total ramp density (ramps/km).

The free-flow speed is the average speed of vehicles in a low traffic flow condition, where drivers can drive in their desired speed and not constrained by the presence of other vehicles. It can be obtained by direct measurement in the field or through estimation by employing the speed limit in the analysed road section as the base speed limit value (80-120 km/h). The base condition for the lane width is 3.65 m or higher. When the lane width is smaller than 3.65 m, then adjustment value should be employed as it negatively affects the free-flow speed (narrow lane). The adjustment value is available in Table 12-20 of HCM 6th Edition. The lateral clearance is measured from the right edge of the travel lane to the nearest lateral obstruction. The base condition for the lateral clearance is 1.83 m. When number of lanes is more than one and the lateral clearance is smaller than the 1.83 m, then adjustment must be made following Table 12-21 in HCM.

2. Adjust the free-flow speed. The free-flow speed adjustment is calculated by Equation 14.

$$FFS_{adj} = FFS \times SAF \qquad \text{(Eq. 14)}$$

Where SAF is the Speed adjustment factor.

Free-flow speed can be adjusted using SAF if an adverse effect on the road segment is observed. HCM gives an example such as when the road condition is icy or snowy, then SAF value is less than 1.0. The SAF value for base condition is 1.0.

3. Determine the capacity. The capacity is calculated with Equation 15.

$$c = 2{,}200 + 10 \times (FFS_{adj} - 50) \qquad \text{(Eq. 15)}$$

Capacity calculation in HCM is based on passenger car equivalent (pc/h/ln), and then converted to mixed vehicle (veh/h/ln) by applying a 20% reduction (Dowling et al., 2016).

4. Adjust the capacity. The adjusted capacity is calculated as follows.

$$c_{adj} = c \times CAF \qquad \text{(Eq. 16)}$$

Where CAF is the Capacity adjustment factor.

The capacity adjustment factor is a calibration parameter used to adjust for local condition such as adverse effect from weather condition, work zones, or incidents, that will have a capacity-reducing impact. The default value is 1.0, and CAF cannot be more than 1.0 as this can only reflect capacity reducing impacts from factors mentioned before.

5. Determine the breakpoint value (veh/h/ln).

Breakpoint is the transition point where speed drops from its free-flow speed value (or *adjusted FFS* value) up to a point where capacity is reached. Before the flow reaches breakpoint, the number of vehicles on the road does not affect the vehicle ability to maintain a certain speed (free movement). After the breakpoint, the speed drops as individual vehicle speed is restrained by the number of vehicles in the road segment. The breakpoint is calculated as follows.

$$BP = \left[1000 + 40 \times \left(75 - FFS_{adj}\right)\right] \times CAF^2 \qquad \text{(Eq. 17)}$$

The breakpoint varies with the free-flow speed. When the free-flow speed increases, the breakpoint decreases. The capacity adjustment factor, if employed, is also affecting the breakpoint. As the capacity is reduced, then breakpoint value is also lower. This implies, when capacity is reduced, individual speed may be affected by the vehicle present in a lower flow condition than the original capacity.

6. Determine the demand flow rate (veh/h/ln).

Demand flow is the number of users (vehicle) who desire to use a given system element during a specific period (typically hourly). To construct the graph, it is typical to start from zero flow up to the flow at capacity (c). The flow-density diagram is shown in Figure 5.

7. Determine the speed. The speed is calculated with Equation 18.

$$S = \begin{cases} FFS_{adj}, & v_p \leq BP \\ FFS_{adj} - \dfrac{\left(FFS_{adj} - \frac{c_{adj}}{D_c}\right)\left(v_p - BP\right)^2}{\left(c_{adj} - BP\right)^2}, & BP < v_p \leq c \end{cases} \qquad \text{(Eq. 18)}$$

v_p indicates the demand flow under the prevailing condition and D_c indicates density at capacity (22 veh/km/ln). Other variables are previously defined.

The methodology described above has several limitations for its applicability, and the limitations are indicated as follows (National Academies of Sciences & Transportation Research Board, 2016).

- Lane controls (to restrict lane changing)
- Extended tunnel or bridge control
- Facilities with an FFS more than 75 mi/h or less than 55 mi/h. Lower FFS values can be achieved by calibrating with a SAF
- Capacity-enhancing effects of ramp metering
- Posted speed limit and enforcement practices
- Presence of intelligent transport system (ITS) related to vehicle or driver guidance
- The influence of downstream queuing on a segment

- Operational effects of oversaturated condition
- Operational effects of construction operations

Undersaturated flow curve example

A speed-flow-density graph for a road section with 120 km/h speed and 1.84 ramps/km were constructed using the above method, as shown in Figure 5. There is only one lane, with a width of more than 3.7 m. It results in a capacity of 1920 veh/h/ln.

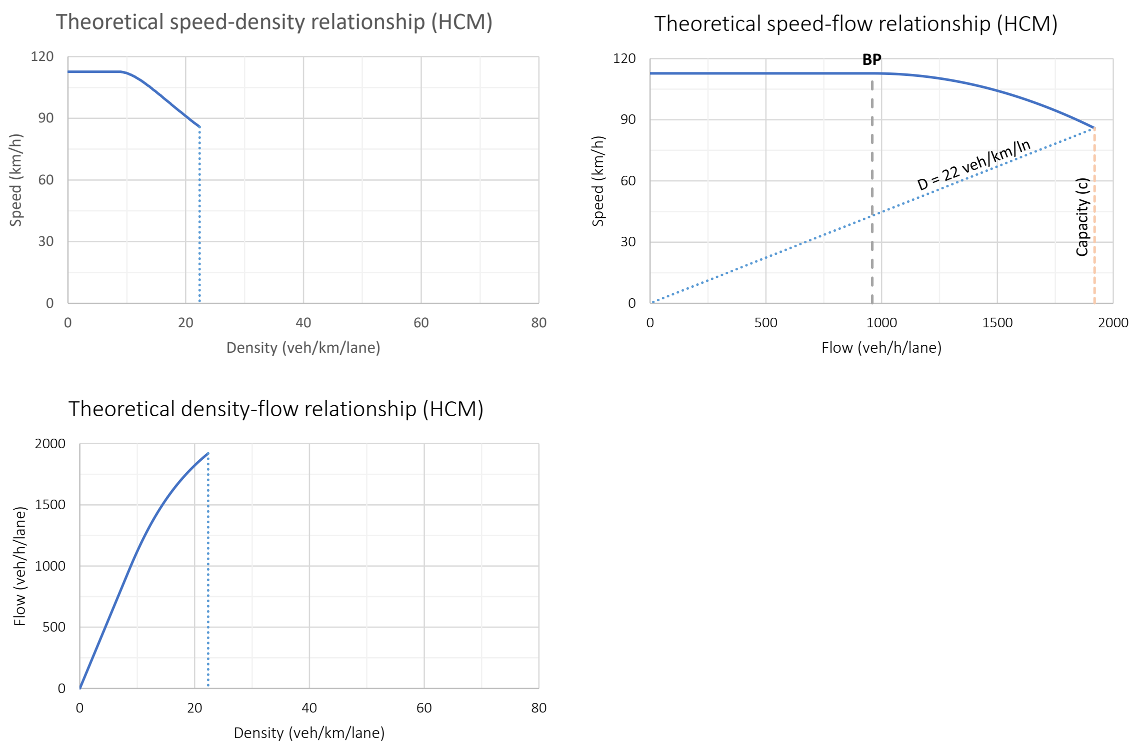


Figure 5. HCM speed-flow-density relationships in undersaturated flow condition (oversaturated conditions excluded from these graphs).

3.2.2 Oversaturated Flow Regime in HCM

Traffic operation under an oversaturated condition in HCM is described as a linear flow-density relationship (National Academies of Sciences & Transportation Research Board, 2016). It is constructed from a user-specified *jam density* and the known value of capacity, defined as flow at a density of 22 veh/km/ln. The jam density is the density where traffic stream completely stops. The default jam density value in the HCM is 94 veh/km/ln, as indicated in Chapter 25 of the Highway Capacity Manual 6th Edition (National Academies of Sciences & Transportation Research Board, 2016). The flow–density relationship is assumed to be linear between these two points, and the speed in a congested segment is obtained from the density in the segment.

Oversaturated flow curve example

An oversaturated flow diagram for a road section with the same characteristics as the road in previous section (120 km/h speed limit with a 1.84 ramps/km) is shown in Figure 6. The undersaturated flow calculation results in a capacity of 1920 veh/h. From the capacity, a linear flow-density curve was created up until density reaches 94 veh/km/ln. The blue line in Figure 6 indicates the undersaturated condition, while the dark green line shows the oversaturated curve.

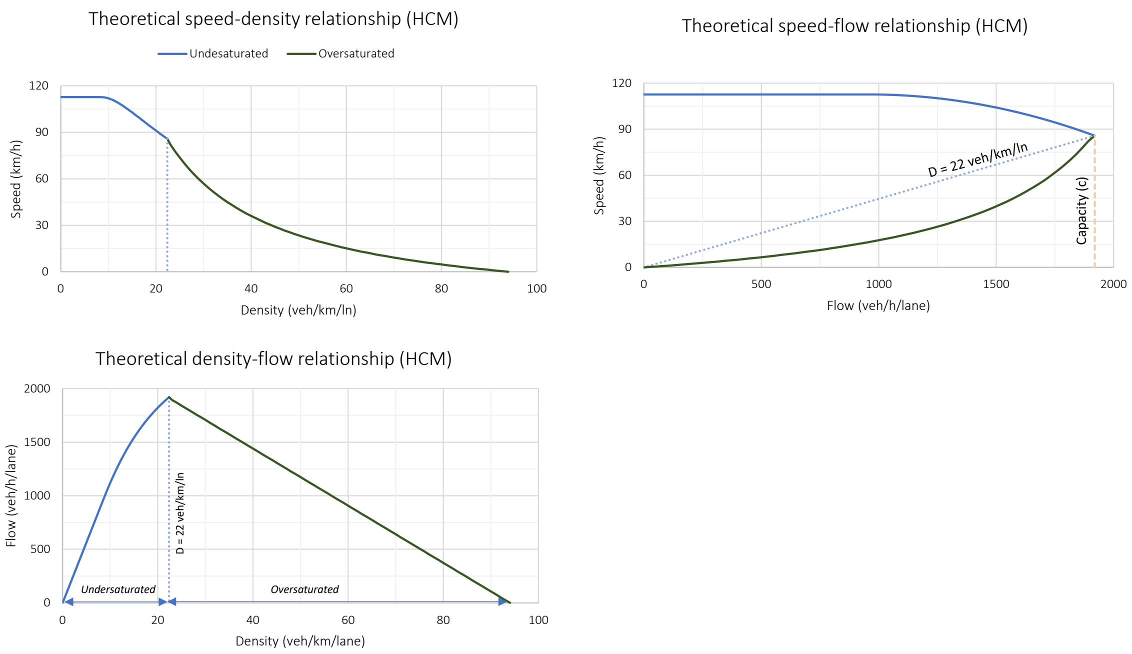


Figure 6. HCM speed-flow-density relationships in undersaturated (blue) and oversaturated (dark green) conditions

3.3 Key Attributes in Wildfire Evacuation

This section presents the main factors present during wildfire evacuation scenarios that may affect the traffic streams during wildfire evacuation. These are the factors that may cause a different traffic dynamic during wildfire evacuation compared with the non-emergency conditions. These factors were identified as factors that affect traffic performance and were derived from reviewing available literatures on wildfire cases. The key factors found in wildfire evacuation cases are:

- **Predominant use of road vehicles to evacuate and the number of vehicles used**. Most evacuees use road vehicles to evacuate due to the scale of the fire, the relatively long distance between the risk area to the refuge area, the need to transport goods, and the trend in household level evacuation (Folk et al., 2019). The use of private vehicles is dominant as observed during Haifa Fire

(Toledo et al., 2018) and Wildfires in California (Wong et al., 2020). In some cases, other means of transportation was also used, such as aircrafts in the Fort McMurray wildfire (Woo et al., 2017), but the use of vehicle is still dominant during most wildfire evacuation.

- **Towing of additional items.** Survey results from evacuees in the California fires indicated that between 6% and 21% of households took towed vehicles during their evacuation (Wong et al., 2020). This is related to the car ownership ratio in the region. Such factor would generate higher number of vehicles more than the number during non-emergency conditions. Rohaert et al. (2022) observed a longer average vehicle length during 2019 Kincade Fire evacuation and suggested the reason may be due to people bringing additional vehicles with them.
- **Potential smoke presence on some routes.** Presence of low-hanging smoke was observed in some wildfire evacuation cases, which means that people had to drive through the smoke during an evacuation. It happened, for example, during the 2019 Tick Fire (Ronchi et al., 2021). A thick smoke above the ground might have also blocked the sun and caused visibility reduction as experienced by the evacuees in the 2009 Black Friday Bushfires (Oloruntoba, 2013).
- **Evacuation route closure.** There were many cases where an evacuation route was blocked and cannot be used. For example, an evacuation route was lost due to the wildfire itself in the Woolsey Fire (Menon et al., 2020). Route was blocked by wildfires debris in Northern California Fire, Camp Fire, and Hill Fire (Wong et al., 2020). A route can also be blocked not only because of environmental impact from the fire, but because at some point evacuees cannot enter a route since it is already congested (i.e., during 2017 Southern California wildfire). Congestion in the major evacuation route can be because it is occupied by the first responders who attempted to fight the fire, such as what happened during 2018 Carr Fire (Wong et al., 2020).
- **Demand and capacity management effort**. Authorities usually implement several strategies ahead of or during disasters evacuation, especially to reduce congestion during mass evacuation. The key strategy often involves managing the evacuation route demand (the number of evacuating vehicles that desire to use the route) and capacity (the number of vehicles that can occupy the route) (Lindell et al., 2019). Phased evacuation order is typically planned to be conducted to distribute evacuation demand over time. However, due to wildfire's rapid spread nature, it is hard to be implemented (Southern California fire, Camp Fire) (Wong et al., 2020). To increase road capacity during wildfire evacuations, counterflow is likely to be implemented (Woolsey Fire, Fort McMurray Fire) (Menon et al., 2020; Woo et al., 2017). Woo et al. (2017)

reported that contraflow operation in Fort McMurray increased road capacity. Another attempt to increase capacity was also observed during Camp Fire evacuation, where evacuees were forced to use road shoulders (Wong et al., 2020).

Some of these attributes are assumed to be directly impacting the key traffic flow parameters (capacity, speed, and density) (e.g., smoke presence, towing other vehicles). Some other attributes may not directly impact the traffic flow parameters, but those are impacting travel demand generated in an evacuation route (e.g., blocked route, contraflow operation).

3.4 Model Enhancement for Wildfire Scenarios - from HCM to WTEC Model

The WTEC model represents an attempt to make the HCM curves more representative of wildfire evacuation by employing these adjustment factors (Equation 14 and 16) onto the assumptions, hence the changes in traffic flow parameters could represent conditions observed during wildfires evacuation. The assumptions that the WTEC model are based on will be outlined in the next sections. Since the methodology presented in Section 3.2 strictly only covers basic highway segment, the WTEC model in this case is intended to only cover basic highway segments.

3.4.1 Assumption 1: Reduction of capacity

Some of the key findings of attributes found in the wildfire evacuation review were assumed to reduce the maximum achievable flow in a road segment. The number of vehicles in the road segment will be smaller compared with the non-emergency situation. This assumption is based on the following evidence.

- *The average spacing and headway increase in wildfire evacuations compared to the non-emergency conditions*. Survey results in the United States indicated that between 6% and 21% of households towed vehicles or other items during a wildfire (Wong et al., 2020). Towing of other items during an evacuation increases average vehicle length and thus, may increase average spacing and headway between vehicles. Spacing is the distance between the front of one vehicle and the front of the subsequent vehicle at a given point in time, and the unit is in meters (distance). Headway is the time between the arrival of one vehicle at a particular location in the segment and the arrival of the next vehicle at that same location, and the unit of headway (s/veh) is in time (seconds or minutes). Meanwhile, clearance is the space between vehicles, and the unit is in meter. Figure 7 illustrates headway, spacing, gap, and clearance between two vehicles. Mean headway is directly related to flow through the relationship in Equation 19 (Daganzo, 1997).

$$q = \frac{3600}{\bar{h}} \qquad \text{(Eq. 19)}$$

with q as flow, and $\bar{h}$ as mean headways.

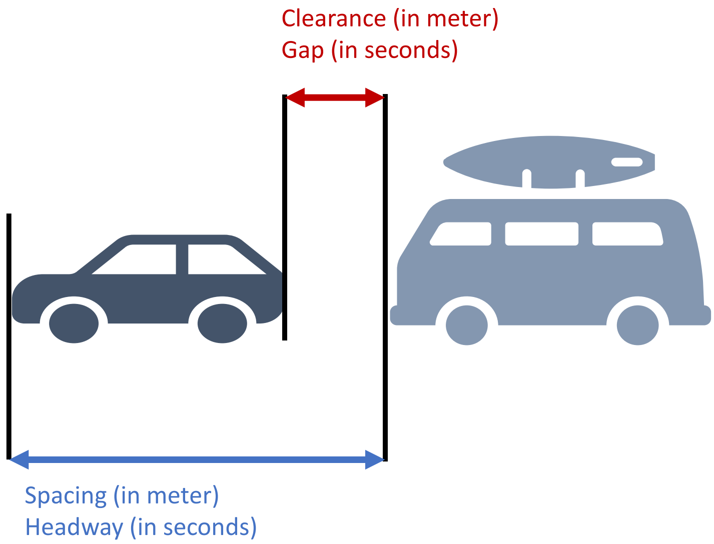


Figure 7. Spacing, headway, clearance, and gap illustration

Relationships in Equation 19 shows that when the average spacing increases, the flow of vehicle decreases. In other words, the number of vehicles that can be present in a road segment during a wildfire condition may be lower than in non-emergency conditions.

Increased headway is also observed in studies investigating individual driving behaviour in environments with reduced visibility. For example, Hoogendoorn et al. (Hoogendoorn et al., 2010) observed that drivers tend to increase headway during a driving simulator experiment in a fog environment. They observed a gradual increase in minimum headway as fog becomes denser (visibility is reduced) and account for this phenomenon to drivers' intention to reduce accident risk. Hence, if low-hanging smoke is present during a wildfire evacuation, visibility might be reduced, and mean spacing and headway may increase. Another study also suggested that capacity drop due to increased headway can be attributed to individual drivers' unfamiliarity with traffic (Brilon et al., 2005). The evacuees may experience unfamiliar traffic since drivers who are not used to driving through smoke may have to do it during wildfire evacuation, or drivers who are not used to driving a recreational vehicle may have to use it during an evacuation (Rohaert et al., 2022). Drivers, therefore, may choose longer headway as they give up the idea of taking over the vehicle in front of them.

More careful driving style is also indicated in previous studies investigating the capacity-reducing impact of adverse weather conditions, such as rain and snow. A study observed that rain reduce freeway capacity by 4%-20% depending on the precipitation rate (light or heavy rain) on the Tokyo Metropolitan Area freeway (Chung et al., 2006). Rakha et al. (Rakha et al., 2008) using data in Seattle, US, observed a capacity reduction during the rainy and snowy conditions, 10% to 11% and 2% to 20%, respectively. A Temporary Loss of Capacity (TLC) study conducted in the US attempted to estimate and quantify capacity loss due to adverse weather effects on highways (Chin, 2004). Therefore, HCM recommended introducing the capacity adjustment factor (CAF) to capture this capacity reduction due to the negative impacts from the environment condition (National Academies of Sciences & Transportation Research Board, 2016).

- *Lower capacity (maximum flow possible) has been observed in hurricane evacuations*. (Dixit & Wolshon, 2014) introduced a "Maximum Evacuation Flow Rate" (MEFR) concept to measure effective capacity during an evacuation. They observed a significant difference between the MEFR during hurricanes evacuation with the capacity observed during a routine traffic. The MEFR observed on a freeway was around 70-85% of the capacity during the normal condition (the average drop from non-emergency to evacuation condition is about 10% to 31%). This finding is also in line with what was observed during Hurricane Katrina, where capacity is dropped by around 37% (Wolshon, 2008). (Dixit & Wolshon, 2014) concluded that the capacity reduction is probably due to downstream queues and different driving behaviour, referring to a study by Brilon et al. (Brilon et al., 2005) that road drivers switched to safer driving and kept longer headways since drivers do not expect to pass the vehicle in front.

The decrease in capacity is employed in the WTEC model curve by applying an adjustment factor in the HCM calculations. Capacity adjustment factor (CAF) is a coefficient introduced in HCM to reflect an adverse weather effect that may reduce the maximum achievable capacity, such as snow in the road segment, heavy rain, or a fog environment. For example, 10% capacity reduction corresponds to a CAF value of 0.9 (90% from the original capacity). The CAF value employed in the 6th edition of HCM depends on the intensity of the rain, snow, and the visibility level (in meter). For instance, as rain's precipitation level increases, the CAF value decreases (the capacity reduction increases).

As discussed above, previous studies showed that the road capacity might be reduced in a wildfire evacuation. However, there is no exact reduction percentage shown in the studies. A range of 10%-30% reduction (CAF value of 0.7-0.9) is then employed in the original HCM model. The CAF value is the user input value when using WTEC model for application. The values used here a simply suggestions derived from the limited literature available. Figure 8 shows the range of capacity reduction that may occur in a wildfire evacuation traffic condition. The dark blue line indicates the original HCM curve from a road with a speed limit of 120 km/h and 1.84 ramps/mi in a non-emergency condition. The other colours indicate WTEC model curves with a reduced capacity.

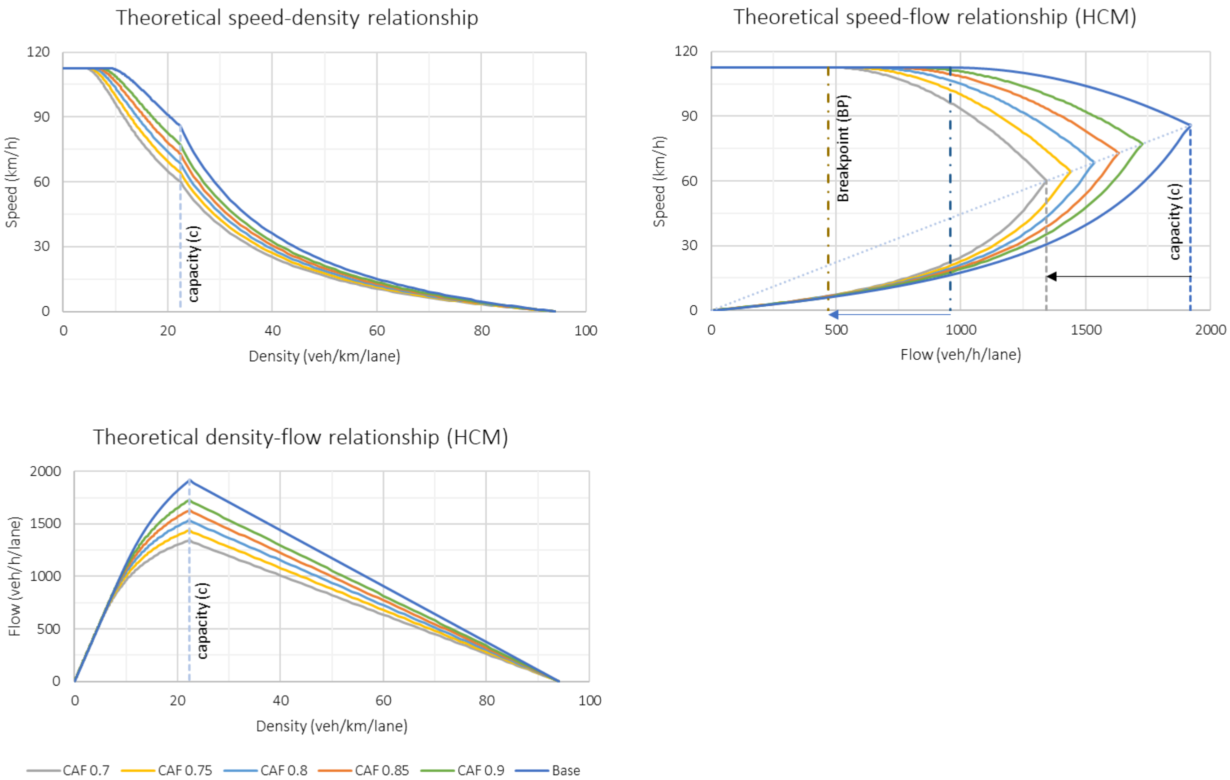


Figure 8. Speed-flow-density diagram with varied CAF values

The impacts of applying CAF are twofold. First, it directly impacts the capacity in the segment. The density at maximum capacity (22 veh/km/ln) peaked at a lower flow than the original (non-emergency) curve. This impact implies that the number of users who can use the analysed road segment during wildfire evacuation will be lower than usual. Since it impacts the maximum achievable flow, the reduction changes the undersaturated and oversaturated regimes. Second, as the capacity reduction increases, the breakpoint gets smaller. The breakpoint is the flow rate value where individual vehicle speed starts to decrease because of other vehicles' presence in the segment. Before the breakpoint is reached, vehicles can maintain their individual speed regardless of the number of vehicles present in the road. To illustrate, smaller breakpoint value means that in non-emergency conditions, each vehicle can maintain its individual speed until density reaches its breakpoint with a value of 959 veh/h/ln. After that, the speed decreases as density gets higher. When the CAF of 0.9 is applied (10% reduction), the breakpoint is lower, so individual speed may be affected by the vehicle present in a smaller density condition (777 veh/h/ln).

3.4.2 Assumption 2: Change in speed

The literature review regarding speed observed during wildfires and other disasters evacuation resulted in mixed findings. Drivers may increase their speed at the beginning due to a sense of urgency (behavioural impact). However, they may eventually decrease their speed if they evacuate in an environment where low-hanging smoke is present or when towing another item (physical impact). The findings found from the literature review are as follows.

- The average speed at the free movement condition (free-flow speed) during an evacuation may be *higher than the average speed during the non-emergency condition*. For example, this is observed in hurricane evacuations where the average speed is higher by 3-4 mi/h (4.8 – 6.4 km/h) than in non-emergency conditions (Dixit & Wolshon, 2014). The possible explanation for the higher speed observed here may be the sense of urgency people experience during an evacuation (Lindell et al., 2019).
- However, during an evacuation in a wildfire event, *individuals may decrease their speed when there is smoke present or when they are carrying another vehicle/item*. In a wildfire evacuation scenario, there is a possibility that drivers will drive in a smoke-filled environment. (Wetterberg et al., 2021) investigated individual driving behaviour during a wildfire evacuation with a smoke-filled environment scenario. The study concluded that people chose lower speed when driving in a smoke-filled environment (Wetterberg et al., 2021). This finding is also supported by other findings related to reduced driving speed with a presence of fog where reduced visibility is observed (Hoogendoorn et al., 2010). Individual speed choice during a reduced visibility environment has been correlated with individual driving skills and driving experience through smoke (Mueller & Trick, 2012; Zhang et al., 2018). Calmer and slower driving behaviour observed during a reduced visibility condition may be explained by drivers' fear of accidents and drivers' intention to avoid collision risk (Wetterberg et al., 2021). A similar conclusion is drawn in psychological research (Schmidt-Daffy, 2013). The study concluded that fear informs the driver's risk of accidents or loss of controls, thus resulting in speed adaptation.

The experimental study recorded physiological and behavioural responses during a driving simulation in a fog environment where visibility is reduced. Additionally, there is evidence that people will likely bring a second vehicle/item during wildfire evacuation (Wong et al., 2020). The impact of this phenomenon might be a reduced mean speed in the road segment, as these vehicles might have the same characteristics as heavy vehicles (such as RVs, minibus, and trucks). This factor depends on the local terrain and elevation condition.

Similar to the capacity adjustment factor (CAF), the HCM recommend introducing a Speed Adjustment Factor (SAF) to the original Free-Flow Speed calculation when adverse weather condition (such as fog, rain, or snow) is observed in the analysis and may impact the free-flow speed. Since a previous study on driving through smoke found a speed decrease of 10% to 30% (Wetterberg et al., 2021), a SAF value of 0.7 to 0.9 was applied to the WTEC model from the original HCM curves. There is also a possibility that people increase their speed during an emergency for about 4% to 6% (Dixit & Wolshon, 2014), therefore a SAF value of 1.03 was also employed. Such an increase means that the free-flow speed will not exceed the speed limit on the road. Figure 9 shows the curve change with different speed adjustment factor (SAF). The blue line indicates the original HCM value, while the other lines show the WTEC model curves using a speed adjustment factor (SAF) with different values.

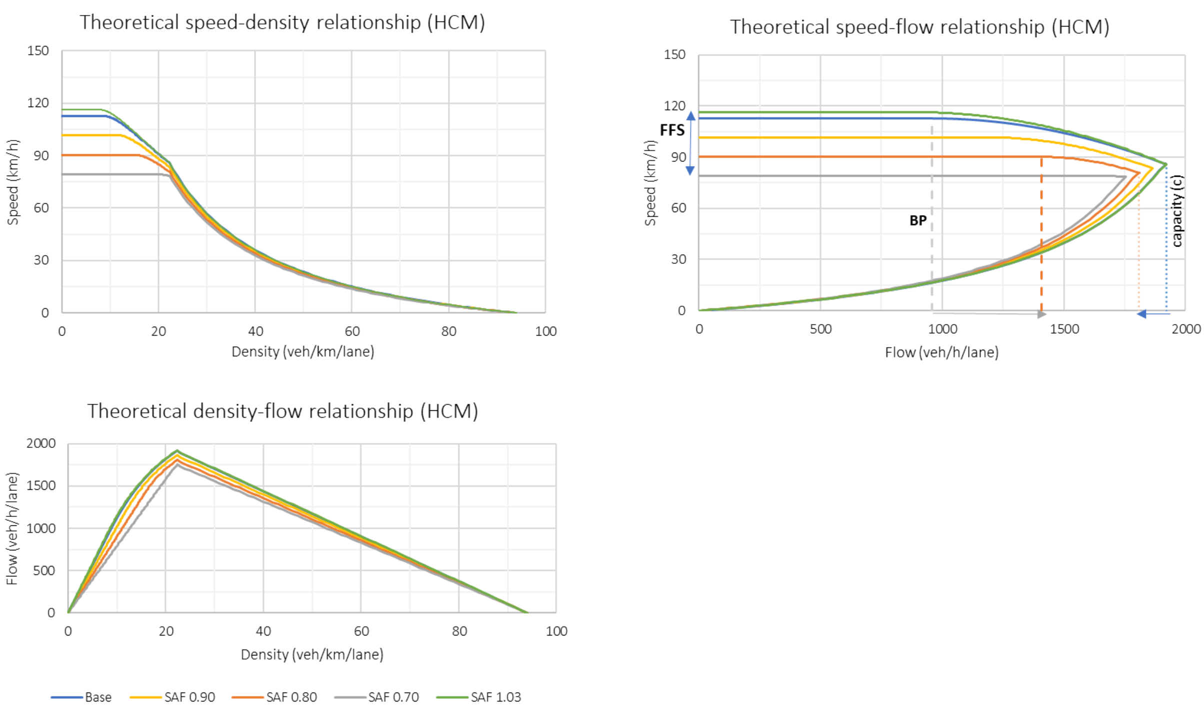


Figure 9. Speed-flow-density relationships with varied SAF values

As seen in Figure 9, the application of SAF impacts the free-flow speed and the maximum flow of vehicles in the road segment. At some point, especially after the density at capacity is reached (22 veh/km/ln), congestion starts to dominate, and the speed would be similar. Clearly, the SAF have a significant impact when there is a free movement.

The breakpoint value is also higher at a higher SAF value, which means lower free-flow speed. *The breakpoint is the value where individual speed is affected by the number of vehicles present in the road segment*. This point is where average speed starts to decrease up to capacity. Interestingly, the breakpoint diminishes when the speed is reduced up to 30% (SAF value of 0.7). The condition turns from free flow to capacity and then oversaturated condition. The density-flow curve is also linear in both undersaturated and oversaturated regimes. This curve looks similar to a truncated triangle flow model by Daganzo (1994).

3.4.3 Assumption 3: Change in jam density

As outlined in Section 3.2.2, the oversaturated flow state in the HCM is governed by the maximum capacity and jam density in the current model. Highway Capacity Manual implied that the jam density value is user-specified (National Academies of Sciences & Transportation Research Board, 2016). However, jam density is the hardest to obtain in the field (Wu et al., 2010) or estimate beforehand (Knoop & Daamen, 2017). Henceforth, an assumption that the maximum density achieved during an evacuation is lower than the non-emergency condition was made. In the WTEC model, the jam density will be assumed to be lower than the theoretical value (the jam density in the HCM is a user-specified value with a default value of 94 veh/km/ln). This assumption is based on the following findings.

- *The observed jam density value in the non-emergency condition is lower than the default HCM value*. Findings from previous research analysing real-world data in the congested region during non-emergency operations and fitting the data with the HCM model show that the jam density value is much lower than the default jam density value suggested by HCM (Xu et al., 2013). The jam density value from the fitted flow density curve in the study is 140 pc/mi/ln (converted to be 69.6 veh/km/ln), lower than the default value of 190 pc/mi/ln from HCM. Xu et al. (2013) mentioned that factors affecting capacity would also affect the flow-density relationship in the congested regime.

- *Congested conditions observed in hurricane evacuation showed that congestion occurs below the default HCM value.* Dixit and Wolshon (2014) observed congestion occurred where density was less than 94 veh/km/ln during hurricane evacuations. From the plotted data observed in Hurricane Ivan, the maximum density during congestion is around 120 veh/mi/ln or about 75 veh/km/ln. In this condition, vehicles moved below 15 mi/h (24 km/h). During congestion, the same maximum density (75 veh/km/ln) was also observed during Hurricane Katrina (Dixit & Wolshon, 2014). The congestion in the evacuation route is possibly due to limited capacity at exit ramps or network destinations (Dixit & Radwan, 2011). This hypothesis is supported by a sensitivity analysis study in a traffic evacuation model that found the outflow has a significant non-linear impact on the total evacuation time (Pel et al., 2010).

The jam density value in the WTEC model is then specified to be lower than the HCM model default value. The jam density employed in other models was reviewed to specify the jam density value. The WUI-NITY project, a wildfire evacuation model, used a jam density value of 100 pc/km/ln (converted into 80 veh/km/ln) following assumptions from the Lighthill-Whitham-Richards (LWR) model (Wahlqvist et al., 2021). The WUI-NITY model has now been updated (Ronchi et al., 2022) to follow linear relationship between speed and density (following Greenshields model). In this model, the jam density is two times the density at capacity (Greenshields, 1934). The input values required to generate the density at capacity are the free-flow speed and flow at capacity data corresponding to road type in Exhibit 129 of the Planning and Preliminary Engineering Application Guides to the HCM (Dowling et al., 2016, p.185). On the other hand, if jam density is calculated using the Greenshields model relationships and strictly follows density at capacity by the HCM (22 veh/km/ln), the jam density would be around 44 veh/km/ln. In the Greenshields model, the jam density is two times the maximum. Therefore, the following WTEC model curve (Figure 10) used a value from 40 veh/km/ln to 80 veh/km/ln as the jam density.

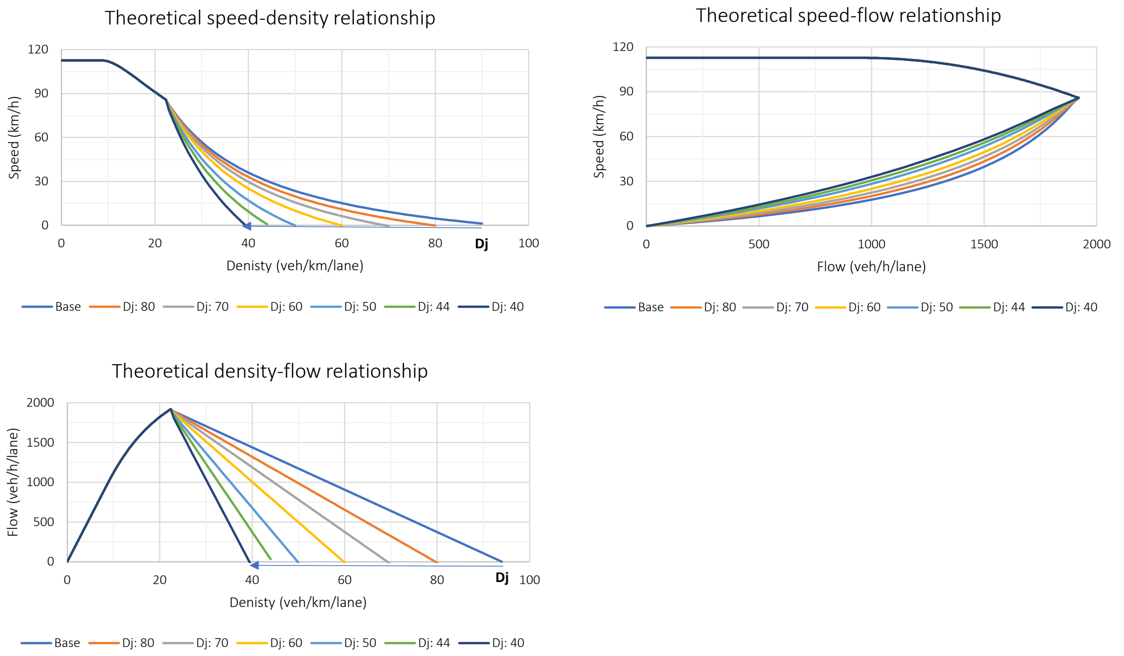


Figure 10. Speed-flow-density relationships with different jam density value

As seen in Figure 10, the jam density value only impacts the curve at the oversaturated regime. As the jam density decreases, the decrease in speed and flow is steeper. This phenomenon means that the speed of vehicles in the smaller jam density curve will be slower with the same density condition. The smaller jam density also concludes that the maximum number of vehicles that can cause all vehicles to not move on the road is also smaller. In that sense, the flow condition is more severe because with fewer vehicles than in normal conditions (HCM original curve), the road is more congested to a point where all vehicles cannot move.

3.4.4 WTEC Model: Combination of assumptions

Assumption 1, 2, and 3 in the WTEC model can be combined to create the WTEC model curve. For example, let us construct a WTEC model curve for a wildfire evacuation condition without any smoke present. Then the following assumptions can be employed to create the curve.

- Assumption 1 of WTEC model: Capacity reduction of 15%. CAF employed is 0.85.
- Assumption 2 of WTEC model: No speed reduction or increase is assumed.
- Assumption 3 of WTEC model: Jam density of 60 veh/km/ln.

The model will be applied to a basic road segment with a speed limit of 120 km/h, 0 ramps/km, and it consists of 1 lane. Figure 11 indicates the speed-flow-density relationships following an WTEC model and the original WTEC model in this road section.

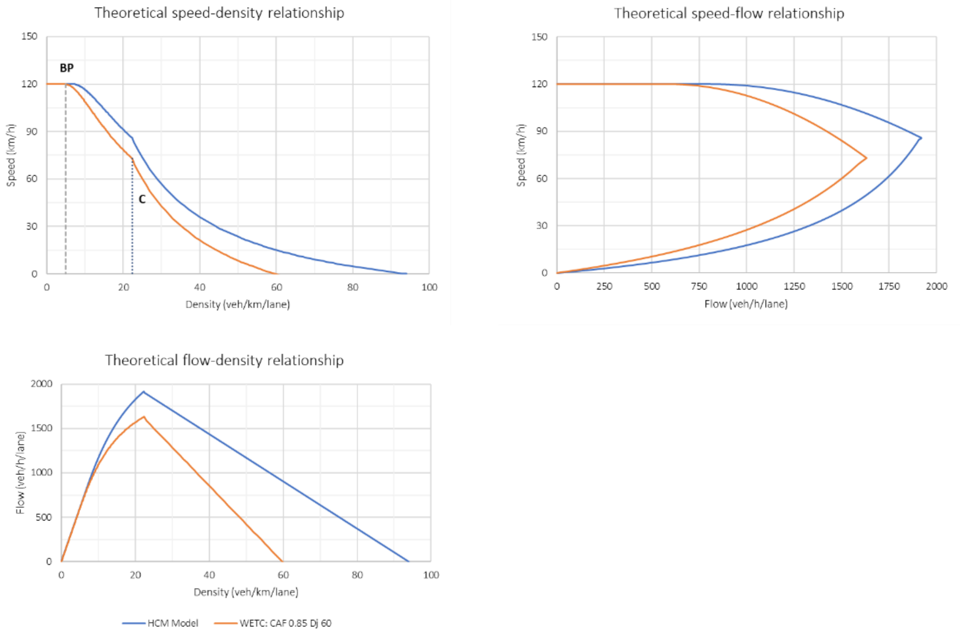


Figure 11. Speed-flow-density relationships by HCM and WTEC models

3.5 Comparison with 2019 Kincade Fire case

Result on the comparison between the HCM and WTEC models with the fitted curves derived from Rohaert et al. (2022) is presented in this section. The road section that was studied in the work of Rohaert et al. (2022) has the following characteristics.

- Basic speed limit : 105 km/h
- Lane width : 3.70 m
- Lateral clearance : > 1.83 m
- Ramp density : 1.07 ramps/km

The above information can be used as the input to generate the HCM and WTEC models.

A speed-flow-density curve of the WTEC model was created following assumptions that reflects the 2019 Kincade Fire evacuation condition:

- Assumption 1: Average headway is longer since many evacuees are towing other items. The capacity reduction factor employed here is 0.85
- Assumption 2: Speed is not reduced since the smoke condition during Kincade Fire was not a low-hanging smoke, so drivers did not evacuate through smoke (Sonoma Operationa Area and the County of Sonoma, 2020).
- Assumption 3: Jam density is lower than the default jam density due to downstream bottleneck. Jam density is 60 veh/km/ln.

Another WTEC model curve was generated by only applying Assumption 1 with more capacity reduction. The assumptions employed are the following.

- Assumption 1: Average headway is longer since many evacuees are towing other items. The capacity reduction factor employed is 0.65.
- Assumption 2: Speed is not reduced since the smoke condition during Kincade Fire was not a low-hanging smoke, so drivers did not evacuate through smoke (Sonoma Operationa Area and the County of Sonoma, 2020).
- Assumption 3: Jam density is lower than the default jam density due to downstream bottleneck. Jam density is 94 veh/km/ln.

Figure 12 shows the speed-density relationship comparison between the different models. The red line indicates a fitted curve to an evacuation data from Rohaert et al. (2022), which is based on the Daganzo (1997) model. The curve is derived using parameters indicated in Rohaert et al. (2022) study as an input to the Daganzo (1997) model. The blue line indicates the HCM curve. The straight grey line indicates the WTEC model with assumption of 15% capacity reduction and jam density value of 60 veh/km/ln. An additional WTEC model curve with a capacity reduction of 35% is also included and indicated with a dashed grey line.

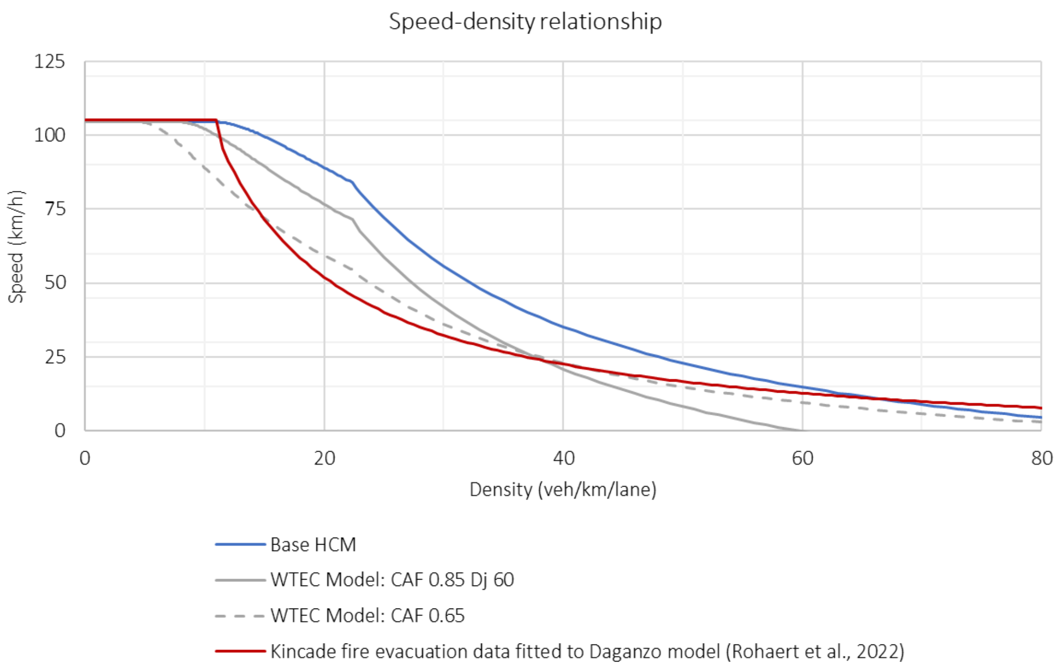


Figure 12. Comparison between HCM and WTEC model curves with Kincade Fire evacuation data

As seen in Figure 12, the HCM curve overestimated the capacity of the road section. The WTEC model with 15% capacity reduction and jam density of 60 veh/km/lane (straight grey line) still seemed to overestimate the capacity. However, the breakpoint value, the value where individual speed is affected by the number of vehicles present in the road segment, is quite similar. On the other hand, the WTEC model with 35% capacity reduction underestimated the breakpoint but shows a broadly similar trend especially when density is higher than density at capacity (22 veh/km/ln). The WTEC model with 15% capacity reduction (straight grey line) agrees well with the Kincade Fire data in the free-flow regime. After the free flow regime, the speed drop does not fit well with the Kincade Fire data since the capacity of the WTEC model is still higher. The Kincade Fire Data fits better with the WTEC model using a capacity reduction of 35% (dashed grey line). This comparison shows that the WTEC model is more similar to the conditions found during a wildfire evacuation scenario. This comparison also suggests that it is worthwhile to further test the WTEC model to other wildfire evacuation cases.

3.6 Test Case Results

The result of the test case will be presented in this section. The test case employed a hypothetical community with a deliberately simple road network, as explained in Section 2.6 to focus on investigating the impacts of the HCM curve modifications. The structure of this section will be as follows.

- The WTEC model assumptions used in the test case will be explained in Section 3.6.1.
- An example of evacuation time estimate calculation for one scenario will be presented in Section 3.6.2.
- The evacuation time estimates from both models (the HCM and WTEC model) for all scenarios (all scenarios are shown in Table 1) will be presented in Section 3.6.3. This section will only present the time estimates for vehicles traveling through Route C. The queue length as an impact from congestion is also estimated and presented in this section.
- Finally, evacuation time estimates derived from the HCM and WTEC models for different Route (A, B, C, D) is presented in Section 3.6.4. This is to assess the impact of applying the models to a different road length.

3.6.1 WTEC Model Configuration

The WTEC model used in the test case will be based on the scenarios (Table 1) and the assumptions used in the WTEC model (Section 3.4). The input values to the model that includes the CAF, SAF, and jam density values in this section are strictly example values to be used in the test case. These values are by no means the recommended values of speed, capacity, and jam density reductions at all wildfire evacuation scenarios—but are provided to enable comparisons to be made.

In the WTEC model, it is assumed that presence of smoke directly affects the WTEC model curve. Since there are cases in the scenario with and without smoke presence that restrict visibility at the driver's level, there were two different WTEC models used in the test case. The physical impact of smoke presence can change the curve shape because the speed is reduced, and the capacity will be further reduced since the driver may increase headway due to smoke. For the scenarios without smoke, the WTEC Model curve employs the following assumption.

- Capacity adjustment factor (CAF) of 0.85 (15% capacity reduction).
- Jam density of 60 veh/km/lane.

There is no speed adjustment factor employed in the above case to see the impact of applying only two assumptions in the WTEC model.

For the scenarios with smoke, the WTEC Model curve employs the following assumptions.

- Capacity adjustment factor (CAF) of 0.80 (20% capacity reduction).
- Jam density of 60 veh/km/lane.
- Speed Adjustment Factor (SAF) of 0.9 (10% reduction).

The capacity is lower in the scenarios where smoke is present, because it is assumed that drivers would increase their spacing more than the condition where visibility is not restricted.

The hypothetical test case assumed a width of 3.7 m, which is the base condition in the HCM methodology. This means that the free-flow speed will not be affected by the geometry of the analysed road section.

As seen in Figure 13, the orange line is the WTEC curve for scenarios with no smoke present, while the green line shows the curves for scenarios with smoke present. For each scenario, capacity is determined with both HCM and the WTEC model curve. The blue line indicates speed-flow curve from the HCM model (which will be the same for all scenarios). The capacity for the HCM curve is 1920 veh/h/ln, the capacity of the WTEC model without smoke present will be 1632 veh/h/ln, and the capacity of the WTEC model with a smoke present is 1517 veh/h/ln.

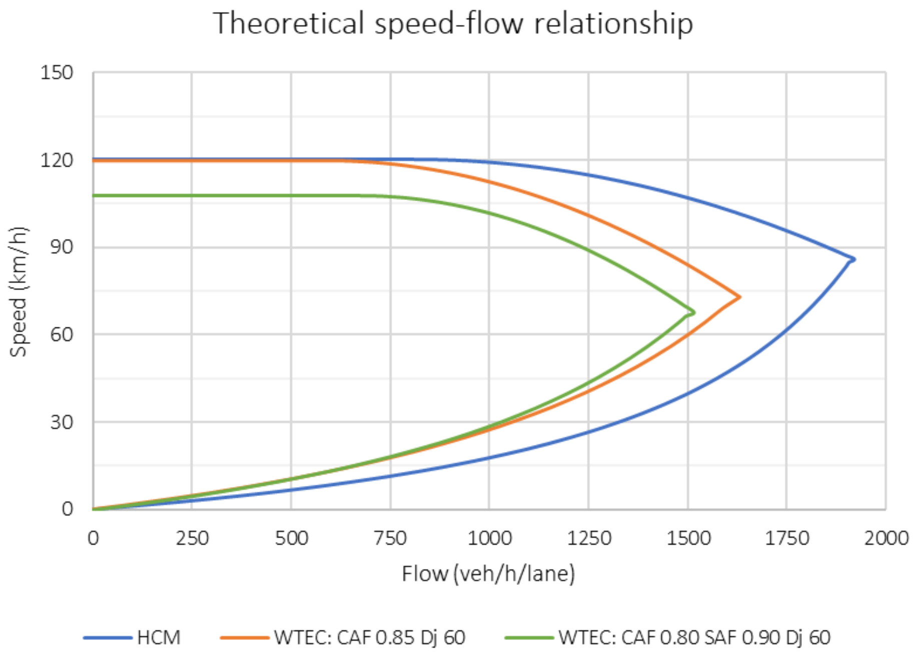
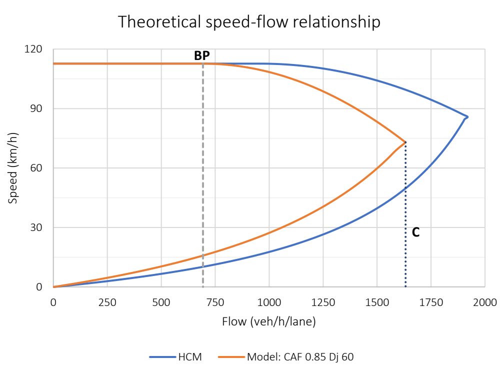
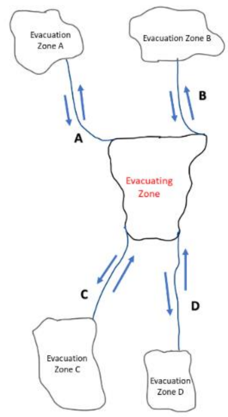
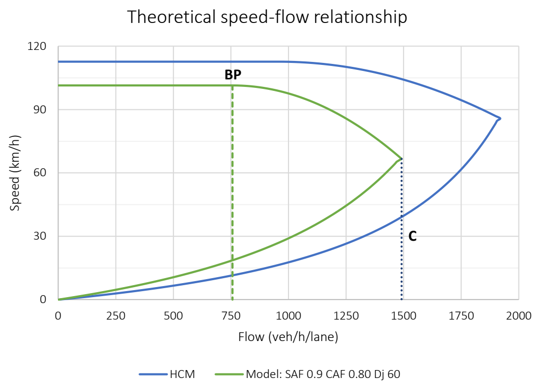
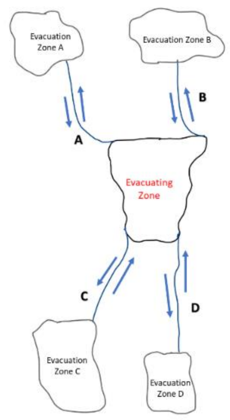
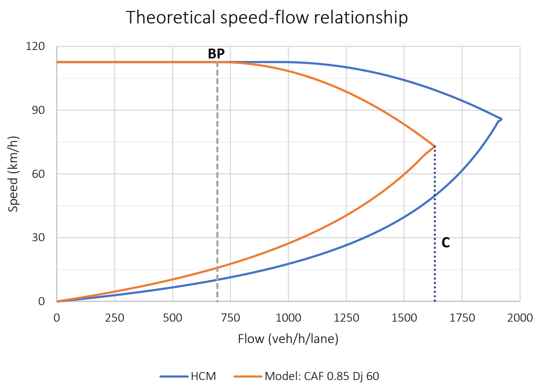
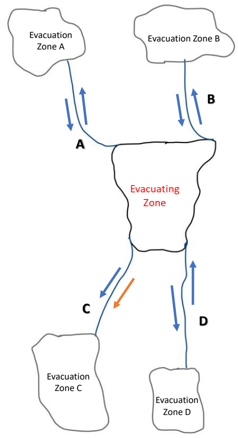
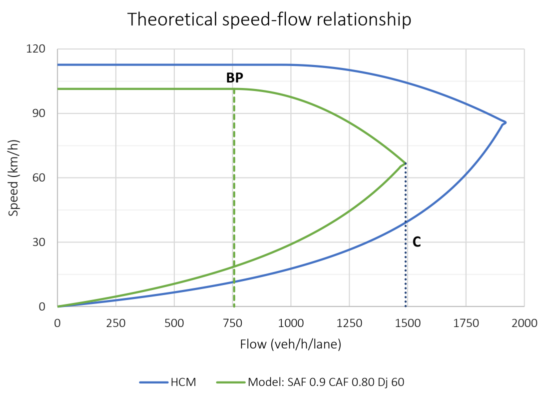
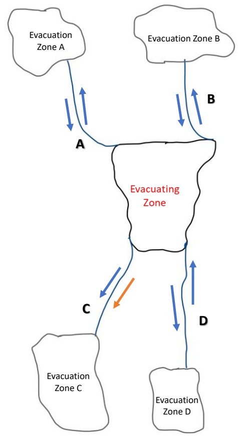


Figure 13. Speed-Flow relationship for cases with and without smoke present

After the WTEC and HCM models were established based on the scenarios, they are used as the basis of evacuation time estimates calculation. For example, the model curve used in Scenario 1 will be different from Scenario 2 as smoke presence will modify the model curve's shapes. Table 3 shows the curves and the road network condition for each scenario. The differences between the scenario pairs in this table is the departure times of the evacuees. In Scenarios 1-8, all evacuees are assumed to try to enter the evacuation routes at the same time. Meanwhile, evacuees in the Scenarios 9-16 have a distributed departure time.

Table 3. Model curve and road network applied to the scenario

Scenario	***Assumptions***	***Speed-flow-density curve***	***Road Network***
1, 9	CAF: 0.85 SAF: 1.00 Dj: 60 veh/km/lane		

<table>
<tr><th>Scenario</th><th>Assumptions</th><th>Speed-flow-density curve</th><th>Road Network</th></tr>
<tr><td>2, 10</td><td>CAF: 0.80
SAF: 0.9
Dj: 60 veh/km/lane</td><td>
</td><td>
</td></tr>
<tr><td>3, 11</td><td>CAF: 0.85
SAF: 1.00
Dj: 60 veh/km/lane</td><td>
</td><td>
</td></tr>
<tr><td>4, 12</td><td>CAF: 0.80
SAF: 0.9
Dj: 60 veh/km/lane</td><td>
</td><td>
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<table>
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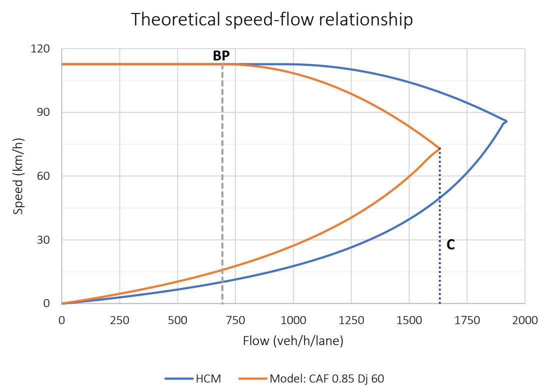
SAF: 1.00
Dj: 60 veh/km/lane</td><td>


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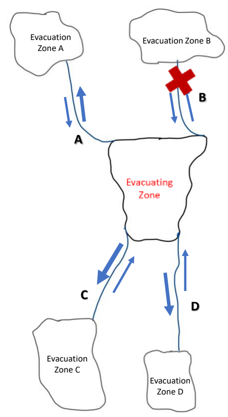

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<tr><td>6, 14</td><td>CAF: 0.80
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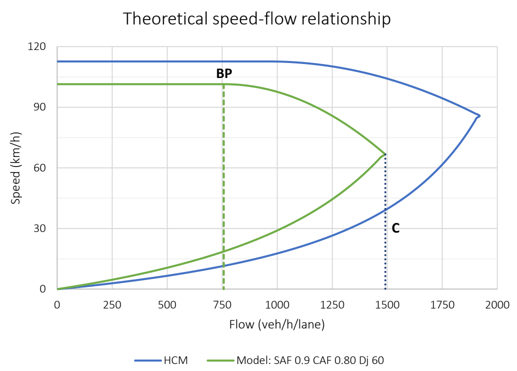
Dj: 60 veh/km/lane</td><td>


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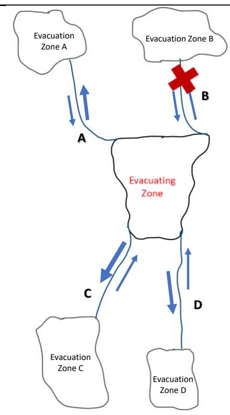

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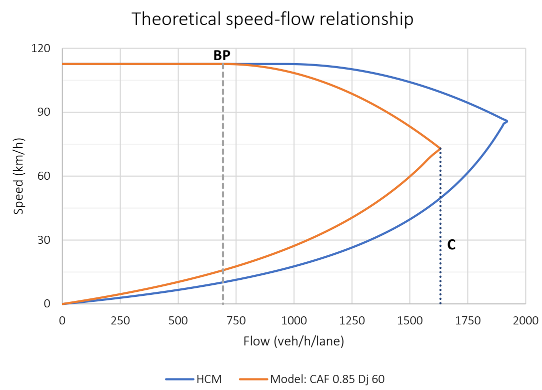
<tr><td>7, 15</td><td>CAF: 0.85
SAF: 1.00
Dj:60 veh/km/lane</td><td>


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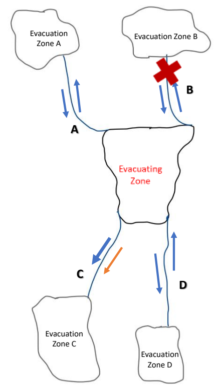
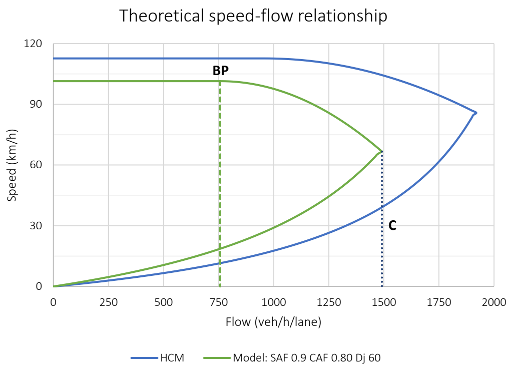
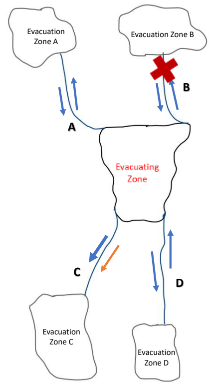


</td></tr>
</table>

Scenario	***Assumptions***	***Speed-flow-density curve***	***Road Network***
8, 16	CAF: 0.80 SAF: 0.9 Dj: 60 veh/km/lane		

3.6.2 Calculation Result Example

This section presents an example of results obtained from both models (HCM and WTEC). Table 4 shows the example of calculation result of Scenario 1 for the analysed Route C. It is derived from the model and the calculation method (Section 2.6.3).

Table 4. Calculation result of Scenario 1

	HCM	**WTEC**
Entrance flow	1745.14	1745.14
Exit Flow (t-1)	0.00	0.00
Carryover demand	0.00	0.00
Demand	1755.25	1755.25
Capacity	1920	1632
d/c	0.91	1.08
ΔUR [min/km]	0.15	0.48
ΔOR [min/km]	0.00	0.66
TR_{FFS} [min/km]	0.50	0.50
TR [min/km]	0.65	1.17
T_{avg} [min]	**16.19**	**29.13**
S_{avg} [km/h]	92.67	51.50
D [veh/km]	18.94	34.08
Demand-capacity	0.00	123.25
Queue length [km]	**0.00**	**3.62**

In scenarios where the departure time is distributed over time (Scenario 9-16), the calculation above is done at each time step (i.e., the entrance flow will be different at each time step). As seen in Table 4, when demand to capacity ratio is above one, the delay rate dominated the travel rate. Therefore, it produces longer travel time. The queue length indicates the total queue length. When there is a significant queue length, evacuating vehicles queued to enter the primary evacuation road inside the evacuating zone, which means the queue will be back to the area at risk. The implication of queueing in a wildfire scenario is people will be vulnerable as they may be exposed to the wildfire that is developing, or they may also be more exposed to smoke. As the wildfire develops over time, there is also a possibility of road closure while evacuees are queuing.

3.6.3 Evacuation Time Estimates for Vehicles Using Route C

This section presents clearance time of Route C (25 km length) for all scenarios, indicated in Table 5. The table also includes the queue lengths of each scenario. The detail calculations for each scenario are available in the Appendices.

Table 5. Test case result of all scenarios corresponding to Route C

Departure Time	***Route Choice***	***Lane reversal***	***Smoke***	***Scenario***	***Clearance Time [h]***		***Result margin***	***Queue Length [km]***	
					HCM	***WTEC***		***HCM***	***WTEC***
Leaving at the same time	Distributed evenly	No	No	1	0.27	0.49	0.22	0.00	3.62
			Yes	2	0.27	0.81	0.54	0.00	4.20
		Yes	No	3	0.23	0.24	0.01	0.00	0.00
			Yes	4	0.23	0.27	0.04	0.00	0.00
	1 Route was blocked	No	No	5	3.25	4.43	1.18	16.85	31.23
			Yes	6	3.25	5.05	1.80	16.85	33.14
		Yes	No	7	1.01	1.80	0.79	4.45	11.78
			Yes	8	1.01	2.22	1.21	4.45	13.69
Rayleigh distribution	Distributed evenly	No	No	9	20.21	20.21	0.00	0.00	0.00
			Yes	10	20.21	20.23	0.02	0.00	0.00
		Yes	No	11	20.21	20.21	0.00	0.00	0.00
			Yes	12	20.21	20.23	0.02	0.00	0.00
	1 Route was blocked	No	No	13	20.21	20.21	0.00	0.00	0.00
			Yes	14	20.21	20.23	0.02	0.00	0.00
		Yes	No	15	20.21	20.21	0.00	0.00	0.00
			Yes	16	20.21	20.23	0.02	0.00	0.00

Clearance time is calculated by adding the departure time with the last travel time in the last time step. In the scenarios where departure time is following Rayleigh distribution, all vehicles entered the evacuation route within 20 hours after the evacuation order was issued. The result margin column indicates the difference in result obtained from HCM and WTEC model. This is obtained by subtracting the result from the WTEC curve with the HCM curve. For example, Scenario 1 concludes that using the WTEC model will result in an 0.22 hour longer clearance time than the HCM model. When queue length is present, it means that vehicles are queueing to enter Route C. The queue length indicates total queue length at each scenario.

To compare the impact of different departure time, Scenarios 1 to 8 are compared with Scenarios 9 to 16. The cases where departure time varied between evacuating vehicles (Scenarios 9-16) shows a little to no difference in the result margin. It is because the vehicles that enter Route C at each time step is very small, and therefore delay is not expected. The little to no difference of HCM and WTEC result does not mean the model does not matter. It shows that the impact from the departure time difference dominates the result. In other scenarios (Scenarios 1-8), the interaction between the population size, departure distribution, and road network means that the movement model employed has a more significant difference.

Figure 14 illustrates the number of vehicles that enter the evacuation Route C at each time step. The orange line denotes Scenario 9, which is the basic case with a Rayleigh distribution departure time. The blue line denotes Scenario 13, with the case where a route was blocked and there was no lane reversal operation. The number of vehicles entering the system was always below the capacity of both models, which means Route C can accommodate all vehicles entering it at each time step without queuing. There is no significant interaction between the vehicles entering the road network with the corresponding traffic network, so the traffic network does not affect the result in this instance.

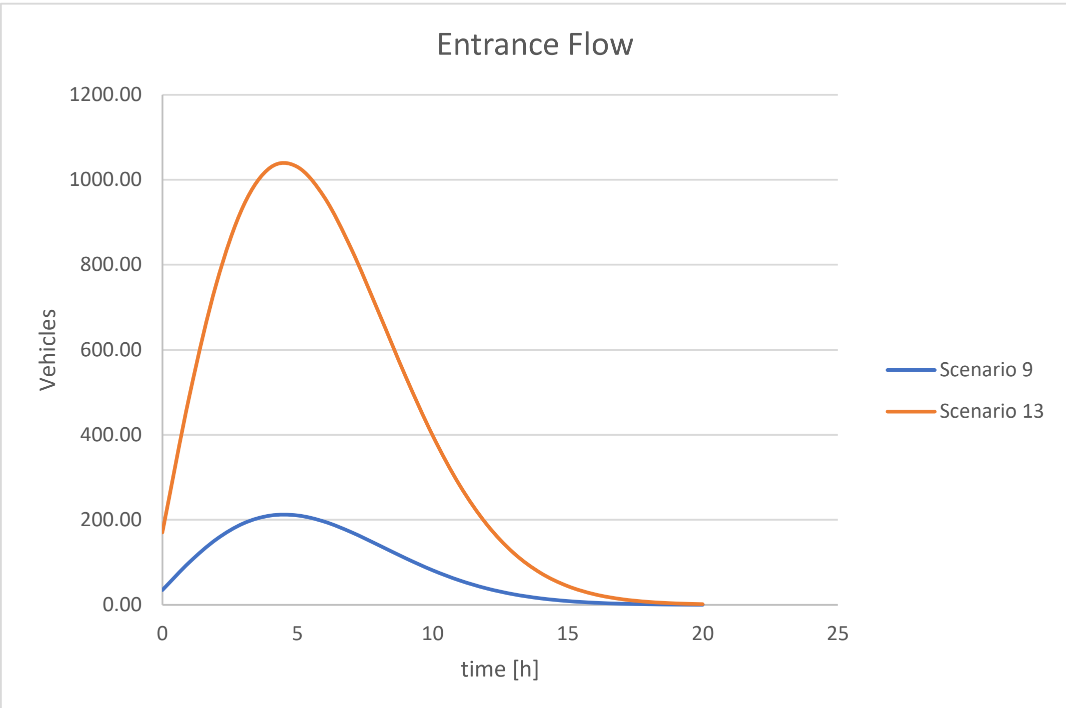


Figure 14. Number of vehicles entering Route C at each time step

The highest result margin is shown in Scenario 6. The longest travel time for both models is also indicated in this scenario. This result is expected since this is a scenario where a road is blocked (Route B) so more vehicles chose Route C – and consequently, the road capacity is more stressed by the demand. A lane reversal order was not applied on Route C. Low-hanging smoke was assumed to be present on Route C, so drivers had to evacuate through smoke and were expected to drive slower and maintained longer headways. There was also a long queue present in this scenario, which might mean that vehicles are queuing in an area where they may be exposed to fire or smoke.

The smallest result difference within the scenarios with 0s departure time is observed in Scenario 3. Such result is expected since there was a lane reversal order in this case, and therefore the number of vehicles present in one lane was smaller compared to other scenarios. Additionally, there was no smoke present in Route C, so evacuees were not expected to drive slower.

To observe the impact of a blocked route, Scenario 1 is compared with Scenario 5, Scenario 2 with Scenario 6, Scenario 3 with 7, and Scenario 4 with 8. When one route (Route B) is blocked, more vehicles will occupy Route C. Vehicles travelling through Route C thus have a longer travel time as more vehicles enter this route than the initial condition (Scenario 1-4). This was observed when employing both models. The result margin between the two models was also higher in cases where a route is blocked (Scenario 5-8). More significant discrepancies between the HCM curve and the model curve results were observed when the road was occupied by more vehicles. This result is expected by comparing the WTEC and the HCM curve in Figure 13. For instance, when the flow of vehicles is about 500 veh/h/lane, the HCM and the model curve will give similar results since vehicles can maintain their individual speeds. However, in scenarios with more vehicles, such as 1000 veh/h/lane, the WTEC curve will give a longer travel time than the HCM curve as a result since vehicles must adjust to a slower speed, while in HCM, the vehicles can still maintain their initial speed.

A similar conclusion is drawn when observing lane reversal or counterflow operation impact on the clearance time estimates. To see the impact of counterflow operation, Scenario 1 is compared with Scenario 3, Scenario 2 with 4, Scenario 5 with 7, and Scenario 6 with 8. When contraflow operation is applied to Route C, three lanes were available to go out of the area at risk to the Evacuation Zone C. Travel time is reduced when contraflow operation is introduced, as the number of vehicles occupying a lane is reduced. For example, when Scenario 5 is compared with Scenario 7, the HCM model result in 2.24 hours decrease in clearance time. While WTEC model result shows 2.63 hours reduction in clearance time. When contraflow was applied, the clearance time differences between the result from HCM and WTEC models were also reduced. For example, the results of the HCM and WTEC models show almost no difference (0.01 hours) compared to the result margin of Scenario 1 which is 0.22 hours.

Table 5 shows that the effect of smoke presence can be observed when comparing Scenario 1 with Scenario 2, Scenario 3 with Scenario 4, Scenario 5 with Scenario 6, and Scenario 7 with Scenario 8. In these comparisons, clearance time increases when smoke is present if travel time is calculated with the WTEC curve. Since the WTEC curves employed to calculate the travel time are different as explained in Section 3.6.1, the travel time is longer when smoke is present (i.e., scenarios with smoke presence have a lower free-flow speed and capacity). Meanwhile the calculation with HCM curve will be the same because effect from smoke was not included in the HCM curve. When comparing Scenario 1 with Scenario 2 in, the speed will be lower for Scenario 2 even with the same number of vehicles (same flow). The difference between the HCM and WTEC model result is also higher when smoke is present. As seen in the model curve employed in Table 3, the model curve has a slower speed than the HCM curve from the beginning, impacting the longer travel time.

The clearance time calculation using the HCM and WTEC curves generally results in a difference. The difference is significant when more vehicles are present in a route (lane). Such a condition can also be observed when, for example, there is a higher vehicle to household ratio than the ratio employed in the test case. Incorporating background traffic, which is the additional traffic on the road by non-evacuation trips, can also cause a significant difference. The difference is also observed when smoke is present since the road capacity and speed are lower in the WTEC model.

3.6.4 Assessing Road Length Impact

To see the model impact on different road length, one scenario was analysed for different road network. The segment in Route A, B, C, D are all basic freeway segment without on- or off-ramp, and the condition is consistent along the segment. The only characteristic difference between the 4 routes is the road length. Table 6 indicates the result of Scenario 1 in Route A, B, C, D.

Table 6. Result of Scenario 1 in all evacuation routes

Scenario	***Route***	***Road length [km]***	***Clearance time [h]***		***Time margin***	***Queue length [km]***	
			HCM	***WTEC***		***HCM***	***WTEC***
1	A	5	0.05	0.32	0.27	0.00	2.05
	B	15	0.16	0.40	0.24	0.00	2.62
	C	25	0.27	0.49	0.22	0.00	3.62
	D	35	0.38	0.57	0.19	0.00	4.32

Table 6 indicates that as the analysed road length decreases, the time margin between the two models increases. The time difference between WTEC and HCM result is the biggest with a road length of 5 km. It is because the delay rate is bigger as the section gets shorter. Additional analysis was also done on shorter length than 5 km, namely for a section with 3 km, 1 km, and 0.5 km. The result shows that the result difference between the two models are around 0.27 to 0.28 hours. As the section gets longer, the impact reduces.

In real conditions, a freeway must have consisted of different segment (i.e., basic segment, segment with on ramps, segment with off ramps, and weaving segment). A basic freeway segment in an evacuation route may be smaller than 25 km. Hence it is possible the clearance time difference between the two models in a varied segment may have been bigger.

4. Discussion

This section presents the summary of the study, a discussion of the study's findings and insights, and discussion of future studies.

As described earlier, this study set out to develop a simple engineering calculation for wildfire evacuation scenarios. To do that, existing mathematical traffic models were studied along with the underlying conditions that need to be captured. The model provided in the Highway Capacity Manual (HCM) was chosen as the basis – primarily, given its widescale use and general acceptance for traffic assessment under non-emergency conditions. However, the HCM model does not provide a specific methodology to describe traffic performance during emergency conditions. Meanwhile, the literature found a difference in traffic capacity during evacuation (Dixit & Wolshon, 2014; Rohaert et al., 2022). Therefore, this study attempted to improve the HCM model to better reflect the traffic performance during wildfire evacuation scenarios. Since the HCM is based on data and studies from the United States, the application of the WTEC model to cases beyond the US should be made with caution.

One of the objectives of this study was to identify the differences between traffic performance during a routine with wildfire evacuation scenarios, to enable more informed modelling of this difference. Key factors affecting traffic performance in wildfire evacuation scenarios were identified by reviewing studies on past wildfire events. Most of the study reporting wildfire requiring vehicle evacuation were from the US. Therefore, these findings must be interpreted with caution when taken out of the US context.

Additionally, a review was also completed on studies about hurricane evacuation traffic performance to support the findings. It is important to note that there are differences that evacuees may encounter during hurricane evacuations, for example, the warning time and the physical condition (i.e., smoke presence on the evacuation route).

After the factors were identified, improvements to the numerical framework of the HCM model were made by reflecting the impact of these factors within the HCM framework. The factors were assumed to impact key traffic performance parameters such as capacity, average speed, and jam density. There are three main assumptions for the WTEC model that were derived from the factors identified by reviewing the literature. One of the critical assumptions was that a road capacity reduces during wildfire evacuation (i.e., lower than its routine). The second assumption was that the average speed might decrease, especially when drivers had to drive through the smoke. The other assumption was that the jam density might be lower than specified in the HCM model. These assumptions were applied to the HCM model to improve it. One assumption or more can be applied to the HCM model based on the conditions during the wildfire. These assumptions were applied by utilising the existing methodology on HCM to reflect an adverse weather effect. A capacity adjustment factor (CAF) can be employed to reduce the capacity. A speed adjustment factor (SAF) can be employed to reflect a decrease in average speed. Finally, a jam density is a user-specified value so that a lower jam density may be employed in the existing model. This improvement changed the curve of the speed-flow-density relationship from the basic HCM model, and the improved model was then referred to as the WTEC model.

Following the development of the WTEC model, this study compared results from the WTEC model and the HCM model to an empirical study (2019 Kincade Fire case). The comparison result, provided in Section 3.5, shows that the HCM model overestimated the traffic capacity during the Kincade Fire evacuation. The Kincade Fire data is more closely approximated by the curves in the WTEC model. Firstly, the reduced speed is mainly assumed when smoke is present in the WTEC model. Since there was no low-hanging smoke during the Kincade Fire evacuation, the assumption was not applied to the WTEC model. The WTEC model then showed a similar free-flow speed value with the Kincade Fire evacuation data. Secondly, the WTEC model models traffic capacity reduction. Two WTEC models were compared. One WTEC model employed a 15% of capacity reduction. This model shows a similar breakpoint value to the Kincade Fire curve. It is a value where individual speed is affected by the number of vehicles present in the road segment. However, the capacity drop in Kincade Fire data is more significant than this WTEC model. The other WTEC model employed a 35% capacity reduction and showed a more similar capacity drop with the Kincade Fire curve, although this WTEC model overestimated the breakpoint value. This result suggested that the capacity reduction may be more than 30%, which was observed in a hurricane evacuations study (Dixit & Wolshon, 2014). Generally, the result enhanced the confidence in the WTEC model. Although the WTEC model was only compared to one set of wildfire data, similar trends might be observed in other wildfire cases.

A set of simple test cases was carried out using the WTEC and HCM models with a twofold purpose. The first purpose is to demonstrate the application of the models to the vehicles' travel time calculation. A queue length estimation can also be made through the calculation. The model estimates the road capacity and the speed at a specific time step with a known demand (i.e., the flow of vehicles at that time step). The second purpose was to assess the difference between results obtained from the HCM and WTEC models.

The significant parameter that influences travel time estimate is the demand-to-capacity ratio. When the demand over capacity ratio is more than one, the road section cannot accommodate all the vehicles that desire to use it, referred to as an oversaturated condition. Table 4 suggests that the delay rate resulting from the oversaturated condition dominates the travel rate and consequently increases travel time. It is also important to note that an assessment of the demand-to-capacity ratio is often used as a method to evaluate traffic performance (Lindell et al., 2019). Therefore, a quick assessment can be made once the traffic model (the WTEC model) has been established.

When a road section is in oversaturated condition, it indicates that a queue may be formed. In a wildfire scenario, a queue means that people are waiting in congestion, but it can also mean that there is a possibility that people might be more vulnerable to wildfire impacts as they wait in the queue. The evacuees might be more likely to be exposed to fires or smoke.

The result from scenarios with distributed response time (Scenarios 9-16) shows that the response time dominates the result. Thus, there are more minor differences between the HCM and the WTEC models. It is because the number of vehicles entering the system is very small at each time step (every hour), so the vehicles do not interact with each other, and therefore they can always maintain their desired speed. During an evacuation, the distributed departure time is often observed as the authorities' effort to manage the travel demand. However, in wildfire evacuation scenarios, delaying departure time might cause negative implications such as the closure of the evacuation route and exposure to fires and smoke as the fire develops (e.g., vehicles trapped in fires during Victoria Black Saturday bushfires (Oloruntoba, 2013)). The outcome of delaying departure time should be taken with caution, considering community's vulnerability is fluctuating as the incident progresses.

Finally, the impact of applying the model into different section lengths was observed to impact the WTEC model's travel time. When the analysed road length reduces, the difference in the capacity-reducing factors (i.e., larger average headway assumption in the WTEC model) has a more considerable effect. The road length used to evaluate all scenarios (Section 3.6.3) was 25 km, and the road has a consistent basic highway segment. However, a highway is likely to be consisted of different segments, with a shorter basic freeway segment length than employed in the test case. Example cases in HCM used a basic freeway segment of around 1.2 km or less along an analysed highway.

This study presents the WTEC model that informs an approach to model traffic performance during a wildfire evacuation. However, it is by no means recommending the input values to use when modelling wildfire evacuation traffic. When more data on traffic during wildfires are available, the model should be suitably configured and validated. Further discussion on limitations of this model and the future work from this study are discussed in the next sections.

5. Limitations

The WTEC model capabilities were set out in the beginning of this study. However, some limitations were found throughout the study. The limitations identified are as follows.

- The WTEC model is derived from assumptions taken from findings of studies reporting wildfire cases requiring vehicle evacuation. However, the majority of studies reporting vehicle evacuation traffic is from the United States, so that some assumptions may not be similar in different regions. Since cross-cultural differences exist in behavioural itineraries before evacuees leave their house for evacuation (i.e., their priorities, time taken to do discrete action) (Vaiciulyte et al., 2021), differences might exist in the factors that were used to derive the WTEC model assumptions. Therefore, the application of the WTEC model's assumption must be taken with caution as different population characteristics may exist. For example, this model heavily relies on the fact that, on average, households may take more than one vehicle to evacuate or carry other items with them. However, this assumption might be unique to the US context since their average vehicles-to-household ratio is more than one. In contrast, Toledo et al. (2018) reported that the number of vehicles to household ratio during the Haifa Fire (in Israel) was less than one (0.89 veh/household) (Toledo et al., 2018). This means that adjustment or calibration is required when more studies reporting vehicle evacuation are available.
- Since the WTEC model is based on the HCM model, the application of this model into road network outside of the United States should be conducted with caution. This is because roads built in other region outside of the US are different, such as, the width and number of lanes in the highway.
- There is only little to no study on observed wildfire evacuation traffic dynamics, so the WTEC model was only compared to one empirical data set (2019 Kincade Fire evacuation traffic dynamics study).
- The WTEC model was only tested on a basic segment. In contrast, a whole highway segment may vary in types (i.e., merge, diverge, weaving), and different segment types require distinct analysis methods.
- The traffic analysis in the WTEC model did not specify the terrain condition when the road segment was inclined or declined. At the same time, the terrain type might also affect the traffic performance (i.e., the road capacity and average speed).
- Shadow evacuation and background traffic were deliberately neglected in the test case, so the impacts of these phenomena were not evaluated. Meanwhile, the impact might be significant to the total clearance time of the population.

- The WTEC model does not include the assumption of evacuation time scale. Evacuation during nighttime may be less likely, but the impact on drivers' visibility (and consequently their driving behaviours) may be significant.
- The engineering calculation proposed here has the advantage of relatively quick assessment time, but the temporal scale is limited. It is static and deterministic. For instance, when the evacuation time window is 24 hours, the road network conditions might change in 24 hours (e.g., a route may be blocked, or contraflow may be in operation in between the 24 hours of evacuation time). Such changes were not implemented in the middle of the test case. The dynamic nature of evacuees' route choice is also out of the scope of this model.
- In the calculation, the time it takes for each household to enter the evacuation road network is assumed to be negligible. However, such an assumption might not be valid if any factor may cause a significant delay. The factor includes congestion in the arterial road inside the area at risk or a roadblock that may cause a detour to another evacuation route.

6. Future Work

The developmental process and the prototype model produced in this study can advise the future work following this study.

The future work in this study should include calibrating and validating the model with other wildfire evacuation cases. It means that calibration is required when more studies reporting vehicle evacuation are available. Moreover, it should be done if studies describing traffic during wildfire evacuation outside of the US are available.

The test case employed in the future study should include more complex—realistic geometry to better represent real-life situations. For instance, the test case only analysed a basic segment in this preliminary work. The test case can include merge, diverge, and weaving segments in future studies. The model can also represent road segments with different terrain conditions (i.e., inclined or declined segments).

Additionally, the model shall be applied to test cases that incorporate background traffic and shadow evacuation. When creating a more realistic test case than what was employed in this study, the Annual Average Daily Traffic (AADT) data can be incorporated as the background traffic of the selected road segment. AADT is the average 24-hour traffic volume at a given location over a full 365 days per year (National Academies of Sciences & Transportation Research Board, 2016). Evacuation during the daytime may include a factor that represents peak hour traffic. Shadow evacuation from regions outside the zone that received mandatory evacuation orders can also be incorporated into the scenarios when testing the model.

7. Conclusions

The threat of wildfire is increasing and expanding due to environmental pressures from climate change (Abatzoglou et al., 2019; Dupuy et al., 2020; Jolly et al., 2015). Recent wildfires have been observed to cause destructions and losses (Kramer et al., 2019; Papathoma-Köhle et al., 2022; Tymstra et al., 2020), and communities living close to or in the wildland areas become more vulnerable to wildfire hazards. The significance of the problem requires communities to prepare for and respond to wildfires. Planning a large-scale evacuation is of great importance since evacuation is one of the most common responses to wildfire hazards. The authorities first need to assess the community's capacity to evacuate to do that. Therefore, the main goal of this study was to develop a method to calculate evacuation time estimates for wildfire evacuation scenarios. The study set out to focus on developing such a method for vehicle movement. A simple evidence-based approach was adopted:

- identification of means of representing traffic conditions in HCM,
- derivation of key performance factors derived from previous large-scale incidents requiring traffic evacuation,
- interpretation of these assumptions using HCM means enabling a modified HCM model (WTEC model) to be produced,
- WTEC and HCM models were applied, and results compared with Kincade wildfire traffic evacuation dataset, enabling insights into WTEC performance and model calibration,
- WTEC and HCM model applied to simple hypothetical case allowing comparison between models and exploring where model results diverge.

A literature review on existing traffic models describing traffic on a macroscopic level was conducted to develop the method. The Highway Capacity Manual (HCM) model was chosen as the base model for this study (National Academies of Sciences & Transportation Research Board, 2016). Since the HCM model focuses its analysis on traffic during non-emergency conditions, the study attempted to improve the HCM model to reflect the conditions during a wildfire evacuation better.

This study produced the WTEC model, which represents an attempt to make the HCM model curves more representative of wildfire evacuation. The assumptions in the WTEC model were based on some factors that might impact traffic performance during evacuations. The factors were derived from reviewing the literature on past wildfire evacuations requiring vehicle movements. Studies on traffic performance during hurricane evacuations were also reviewed as a supplement where little to no data exists on wildfire evacuation cases. The assumptions of the WTEC model were applied to the basic HCM model by incorporating CAF and SAF values and changing the jam density value. The numerical improvement followed the methodology outlined in the HCM for specific scenarios, such as when the analysed road is snowy or in a low visibility condition. In this case, it is adapted to represent conditions found during wildfire evacuations. In the WTEC model, the capacity and free-flow speed reductions can be employed using the CAF and SAF. The study suggested a range of values for the capacity and speed adjustment factors. The same goes for the jam density value.

The HCM and WTEC models were compared to the empirical dataset during the 2019 Kincade fire evacuation. The result suggested that the HCM model overestimated the traffic capacity during the Kincade fire evacuation. Meanwhile, the WTEC model fits better with the dataset. Although the model was only compared to one publicly available dataset, the comparison result enhances the WTEC model confidence. Therefore, this study suggests testing the WTEC model on more wildfire evacuation datasets.

This study also applied both HCM and WTEC models to a set of a hypothetical test case. In the test case, the evacuation times of vehicles using both models were estimated using a method used in the HCM. Additionally, the method can also estimate queue length. The evacuation time estimate results indicate a substantial difference between the two models, mainly when the number of evacuating vehicles is significant and exceeds the traffic capacity employed in the model.

This study presents the developmental model for estimating the evacuation time during wildfire evacuation scenarios. Although the model produced (the WTEC model) is still a prototype, it does represent the first attempt (at least the first publicly available model given the review conducted) to produce a simple set of engineering calculations that can capture the impact of a wildfire emergency on traffic performance during an evacuation of a community. The WTEC model assessment can still inform the authorities or emergency planners' insight into the evacuation route capacity. Therefore, they can make a more informed decisions on planning and managing traffic during wildfire evacuations. The developmental process and the prototype model produced in this study can also advise the future work following this study.

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Appendices

This section presents the ravel time and queue length calculation for each scenario presented in this work.

Scenario 1 in Route C

	HCM	**WTEC**
Entrance flow	1755.25	1755.25
Exit Flow (t-1)	0.00	0.00
Carryover demand	0.00	0.00
Demand	1755.25	1755.25
Capacity	1920	1632
d/c	0.91	1.08
ΔUR [min/km]	0.15	0.00
ΔOR [min/km]	0.00	0.66
TR_{FFS} [min/km]	0.50	0.50
TR [min/km]	0.65	1.17
T_{avg} [min]	**16.19**	**29.13**
S_{avg} [km/h]	92.67	51.50
D [veh/km]	18.94	34.08
Demand-capacity	0.00	123.25
Queue length [km]	**0.00**	**3.62**

Scenario 2 in Route C

	HCM	**WTEC**
Entrance flow	1755.25	1755.25
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	1755.25	1755.25
Capacity	1920.00	1517.12
d/c	0.91	1.16
ΔUR [min/km]	0.15	0.00
ΔOR [min/km]	0.00	1.38
TR_{FFS} [min/km]	0.50	0.56
TR [min/km]	0.65	1.94
T_{avg} [min]	16.19	48.43
S_{avg} [km/h]	92.67	30.97
D [veh/km]	18.94	56.67
Demand-capacity	0.00	238.13
Queue length [km]	0.00	4.20

Scenario 3 in Route C

	HCM	WTEC
Entrance flow	1170.17	1170.17
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	1170.17	1170.17
Capacity	1920.00	1632.00
d/c	0.61	0.72
ΔUR [min/km]	0.06	0.07
ΔOR [min/km]	0.00	0.00
TR_{FFS} [min/km]	0.50	0.50
TR [min/km]	0.56	0.57
T_{avg} [min]	13.90	14.24
S_{avg} [km/h]	107.91	105.33
D [veh/km]	10.84	11.11
Demand-capacity	0.00	0.00
Queue length [km]	0.00	0.00

Scenario 4 in Route C

	HCM	WTEC
Entrance flow	1170.17	1170.17
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	1170.17	1170.17
Capacity	1920.00	1517.12
d/c	0.61	0.77
ΔUR [min/km]	0.06	0.08
ΔOR [min/km]	0.00	0.00
TR_{FFS} [min/km]	0.50	0.56
TR [min/km]	0.56	0.64
T_{avg} [min]	13.90	15.95
S_{avg} [km/h]	107.91	94.04
D [veh/km]	10.84	12.44
Demand-capacity	0.00	0.00
Queue length [km]	0.00	0.00

Scenario 5 in Route C

	HCM	WTEC
Entrance flow	3510.51	3510.51
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	3510.51	3510.51
Capacity	1920.00	1632.00
d/c	1.83	2.15
ΔUR [min/km]	5.41	0.00
ΔOR [min/km]	7.29	10.13
TR_{FFS} [min/km]	0.50	0.50
TR [min/km]	7.79	10.63
T_{avg} [min]	194.75	265.74
S_{avg} [km/h]	7.70	5.64
D [veh/km]	94.40	60.15
Demand-capacity	1590.51	1878.51
Queue length [km]	16.85	31.23

Scenario 6 in Route C

	HCM	WTEC
Entrance flow	3510.51	3510.51
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	3510.51	3510.51
Capacity	1920.00	1517.12
d/c	1.83	2.31
ΔUR [min/km]	5.41	0.00
ΔOR [min/km]	7.29	11.56
TR_{FFS} [min/km]	0.50	0.56
TR [min/km]	7.79	12.12
T_{avg} [min]	194.75	302.96
S_{avg} [km/h]	7.70	4.95
D [veh/km]	94.40	60.15
Demand-capacity	1590.51	1993.39
Queue length [km]	16.85	33.14

Scenario 7 in Route C

	HCM	WTEC
Entrance flow	2340.34	2340.34
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	2340.34	2340.34
Capacity	1920.00	1632.00
d/c	1.22	1.43
ΔUR [min/km]	0.34	0.00
ΔOR [min/km]	1.93	3.82
TR_{FFS} [min/km]	0.50	0.50
TR [min/km]	2.43	4.32
T_{avg} [min]	60.66	108.00
S_{avg} [km/h]	24.73	13.89
D [veh/km]	94.40	60.15
Demand-capacity	420.34	708.34
Queue length [km]	4.45	11.78

Scenario 8 in Route C

	HCM	WTEC
Entrance flow	2340.34	2340.34
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	2340.34	2340.34
Capacity	1920.00	1517.12
d/c	1.22	1.54
ΔUR [min/km]	0.34	0.00
ΔOR [min/km]	1.93	4.78
TR_{FFS} [min/km]	0.50	0.56
TR [min/km]	2.43	5.33
T_{avg} [min]	60.66	133.28
S_{avg} [km/h]	24.73	11.25
D [veh/km]	94.40	60.15
Demand-capacity	420.34	823.22
Queue length [km]	4.45	13.69

Scenario 9 in Route C

t (h)	Entrance flow	Exit Flow	Carryover	Demand	d/c_HCM	d/c_MKJ	UR_HCM	UR_MKJ	OR_HCM	OR_MKJ	TR_HCM	TR_MKJ	T_HCM	T_MKJ	S_HCM	S_MKJ	D_HCM	D_MKJ	Exit Flow
0.00	34.76	0.00	0.00	34.76	0.02	0.02	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.29	0.29	34.76
1.00	100.19	0.00	0.00	100.19	0.05	0.06	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.83	0.84	100.19
2.00	154.19	0.00	0.00	154.19	0.08	0.09	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.28	1.29	154.19
3.00	191.54	0.00	0.00	191.54	0.10	0.12	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.60	1.60	191.54
4.00	209.96	0.00	0.00	209.96	0.11	0.13	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.75	1.75	209.96
5.00	210.24	0.00	0.00	210.24	0.11	0.13	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.75	1.75	210.24
6.00	195.61	0.00	0.00	195.61	0.10	0.12	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.63	1.63	195.61
7.00	170.74	0.00	0.00	170.74	0.09	0.10	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.42	1.42	170.74
8.00	140.66	0.00	0.00	140.66	0.07	0.09	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.17	1.17	140.66
9.00	109.81	0.00	0.00	109.81	0.06	0.07	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.92	0.92	109.81
10.00	81.47	0.00	0.00	81.47	0.04	0.05	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.68	0.68	81.47
11.00	57.55	0.00	0.00	57.55	0.03	0.04	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.48	0.48	57.55
12.00	38.77	0.00	0.00	38.77	0.02	0.02	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.32	0.32	38.77
13.00	24.94	0.00	0.00	24.94	0.01	0.02	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.21	0.21	24.94
14.00	15.33	0.00	0.00	15.33	0.01	0.01	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.13	0.13	15.33
15.00	9.01	0.00	0.00	9.01	0.00	0.01	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.08	0.08	9.01
16.00	5.07	0.00	0.00	5.07	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.04	0.04	5.07
17.00	2.73	0.00	0.00	2.73	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.02	0.02	2.73
18.00	1.41	0.00	0.00	1.41	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.01	0.01	1.41
19.00	0.70	0.00	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.01	0.01	0.70
20.00	0.33	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.00	0.00	0.33
21.00	-	0.00	0.00		0.00	0.00	0.00				0.50	0.50	12.50	12.51	120.00	119.90	0.00	0.00	0.00

Scenario 10 in Route C

t (h)	Entrance flow	Exit Flow	Carryover	Demand	d/c_HCM	d/c_MKJ	UR_HCM	UR_MKJ	OR_HCM	OR_MKJ	TR_HCM	TR_MKJ	T_HCM	T_MKJ	S_HCM	S_MKJ	D_HCM	D_MKJ	Exit Flow
0.00	35.48	0.00	0.00	35.48	0.02	0.02	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.30	0.3288236	35.4822092
1.00	102.29	0.00	0.00	102.29	0.05	0.07	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.85	0.94791711	102.286432
2.00	157.41	0.00	0.00	157.41	0.08	0.10	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.31	1.45878522	157.412429
3.00	195.54	0.00	0.00	195.54	0.10	0.13	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.63	1.8120815	195.5354
4.00	214.35	0.00	0.00	214.35	0.11	0.14	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.79	1.98639952	214.34545
5.00	214.63	0.00	0.00	214.63	0.11	0.14	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.79	1.98905694	214.632203
6.00	199.69	0.00	0.00	199.69	0.10	0.13	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.66	1.85060746	199.692602
7.00	174.31	0.00	0.00	174.31	0.09	0.11	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.45	1.61534232	174.30596
8.00	143.60	0.00	0.00	143.60	0.07	0.09	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.20	1.33079284	143.601217
9.00	112.11	0.00	0.00	112.11	0.06	0.07	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.93	1.03893684	112.108054
10.00	83.17	0.00	0.00	83.17	0.04	0.05	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.69	0.77075183	83.1691444
11.00	58.75	0.00	0.00	58.75	0.03	0.04	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.49	0.5444631	58.7511156
12.00	39.58	0.00	0.00	39.58	0.02	0.03	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.33	0.36678493	39.5784837
13.00	25.46	0.00	0.00	25.46	0.01	0.02	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.21	0.2359128	25.4565285
14.00	15.65	0.00	0.00	15.65	0.01	0.01	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.13	0.14500645	15.6471402
15.00	9.20	0.00	0.00	9.20	0.00	0.01	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.08	0.08523888	9.1978304
16.00	5.17	0.00	0.00	5.17	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.04	0.04794703	5.17379718
17.00	2.79	0.00	0.00	2.79	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.02	0.02582097	2.78625042
18.00	1.44	0.00	0.00	1.44	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.01	0.01331826	1.43712718
19.00	0.71	0.00	0.00	0.71	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.01	0.00658167	0.71020551
20.00	0.34	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.00	0.00311721	0.3363672

Scenario 11 in Route C

t (h)	Entrance flow	Exit Flow	Carryover	Demand	d/c_HCM	d/c_MKJ	UR_HCM	UR_MKJ	OR_HCM	OR_MKJ	TR_HCM	TR_MKJ	T_HCM	T_MKJ	S_HCM	S_MKJ	D_HCM	D_MKJ	Exit Flow
0.00	23.65	0.00	0.00	23.65	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.21	0.21	23.65
1.00	68.19	0.00	0.00	68.19	0.04	0.04	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.61	0.61	68.19
2.00	104.94	0.00	0.00	104.94	0.05	0.06	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.93	0.93	104.94
3.00	130.36	0.00	0.00	130.36	0.07	0.08	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	1.16	1.16	130.36
4.00	142.90	0.00	0.00	142.90	0.07	0.09	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	1.27	1.27	142.90
5.00	143.09	0.00	0.00	143.09	0.07	0.09	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	1.27	1.27	143.09
6.00	133.13	0.00	0.00	133.13	0.07	0.08	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	1.18	1.18	133.13
7.00	116.20	0.00	0.00	116.20	0.06	0.07	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	1.03	1.03	116.20
8.00	95.73	0.00	0.00	95.73	0.05	0.06	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.85	0.85	95.73
9.00	74.74	0.00	0.00	74.74	0.04	0.05	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.66	0.66	74.74
10.00	55.45	0.00	0.00	55.45	0.03	0.03	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.49	0.49	55.45
11.00	39.17	0.00	0.00	39.17	0.02	0.02	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.35	0.35	39.17
12.00	26.39	0.00	0.00	26.39	0.01	0.02	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.23	0.23	26.39
13.00	16.97	0.00	0.00	16.97	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.15	0.15	16.97
14.00	10.43	0.00	0.00	10.43	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.09	0.09	10.43
15.00	6.13	0.00	0.00	6.13	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.05	0.05	6.13
16.00	3.45	0.00	0.00	3.45	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.03	0.03	3.45
17.00	1.86	0.00	0.00	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.02	0.02	1.86
18.00	0.96	0.00	0.00	0.96	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.01	0.01	0.96
19.00	0.47	0.00	0.00	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.00	0.00	0.47
20.00	0.22	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.00	0.00	0.22

Scenario 12 in Route C

t (h)	Entrance flow	Exit Flow	Carryover	Demand	d/c_HCM	d/c_MKJ	UR_HCM	UR_MKJ	OR_HCM	OR_MKJ	TR_HCM	TR_MKJ	T_HCM	T_MKJ	S_HCM	S_MKJ	D_HCM	D_MKJ	Exit Flow
0.00	23.65	0.00	0.00	23.65	0.01	0.02	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.21	0.23	23.65
1.00	68.19	0.00	0.00	68.19	0.04	0.05	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.61	0.67	68.19
2.00	104.94	0.00	0.00	104.94	0.05	0.07	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.93	1.03	104.94
3.00	130.36	0.00	0.00	130.36	0.07	0.09	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	1.16	1.29	130.36
4.00	142.90	0.00	0.00	142.90	0.07	0.10	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	1.27	1.41	142.90
5.00	143.09	0.00	0.00	143.09	0.07	0.10	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	1.27	1.41	143.09
6.00	133.13	0.00	0.00	133.13	0.07	0.09	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	1.18	1.31	133.13
7.00	116.20	0.00	0.00	116.20	0.06	0.08	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	1.03	1.15	116.20
8.00	95.73	0.00	0.00	95.73	0.05	0.06	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.85	0.94	95.73
9.00	74.74	0.00	0.00	74.74	0.04	0.05	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.66	0.74	74.74
10.00	55.45	0.00	0.00	55.45	0.03	0.04	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.49	0.55	55.45
11.00	39.17	0.00	0.00	39.17	0.02	0.03	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.35	0.39	39.17
12.00	26.39	0.00	0.00	26.39	0.01	0.02	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.23	0.26	26.39
13.00	16.97	0.00	0.00	16.97	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.15	0.17	16.97
14.00	10.43	0.00	0.00	10.43	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.09	0.10	10.43
15.00	6.13	0.00	0.00	6.13	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.05	0.06	6.13
16.00	3.45	0.00	0.00	3.45	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.03	0.03	3.45
17.00	1.86	0.00	0.00	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.02	0.02	1.86
18.00	0.96	0.00	0.00	0.96	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.01	0.01	0.96
19.00	0.47	0.00	0.00	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.00	0.00	0.47
20.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.00	0.00	0.00

Scenario 13 in Route C

t (h)	Entrance flow	Exit Flow	Carryover	Demand	d/c_HCM	d/c_MKJ	UR_HCM	UR_MKJ	OR_HCM	OR_MKJ	TR_HCM	TR_MKJ	T_HCM	T_MKJ	S_HCM	S_MKJ	D_HCM	D_MKJ	Exit Flow
0.00	170.31	0.00	0.00	170.31	0.09	0.10	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.42	1.42	170.31
1.00	490.97	0.00	0.00	490.97	0.26	0.30	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	4.09	4.10	490.97
2.00	755.58	0.00	0.00	755.58	0.39	0.46	0.00	0.01	0.00	0.00	0.50	0.51	12.50	12.64	120.00	118.71	6.30	6.37	755.58
3.00	938.57	0.00	0.00	938.57	0.49	0.58	0.00	0.02	0.00	0.00	0.50	0.52	12.50	13.09	120.00	114.63	7.82	8.19	938.57
4.00	1028.86	0.00	0.00	1028.86	0.54	0.63	0.04	0.04	0.00	0.00	0.54	0.54	13.55	13.45	110.67	111.56	9.30	9.22	1028.86
5.00	1030.23	0.00	0.00	1030.23	0.54	0.63	0.04	0.04	0.00	0.00	0.54	0.54	13.56	13.45	110.65	111.51	9.31	9.24	1030.23
6.00	958.52	0.00	0.00	958.52	0.50	0.59	0.00	0.03	0.00	0.00	0.50	0.53	12.50	13.16	120.00	114.02	7.99	8.41	958.52
7.00	836.67	0.00	0.00	836.67	0.44	0.51	0.00	0.01	0.00	0.00	0.50	0.51	12.50	12.79	120.00	117.26	6.97	7.14	836.67
8.00	689.29	0.00	0.00	689.29	0.36	0.42	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.56	120.00	119.47	5.74	5.77	689.29
9.00	538.12	0.00	0.00	538.12	0.28	0.33	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	4.48	4.49	538.12
10.00	399.21	0.00	0.00	399.21	0.21	0.24	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	3.33	3.33	399.21
11.00	282.01	0.00	0.00	282.01	0.15	0.17	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	2.35	2.35	282.01
12.00	189.98	0.00	0.00	189.98	0.10	0.12	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.58	1.58	189.98
13.00	122.19	0.00	0.00	122.19	0.06	0.07	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	1.02	1.02	122.19
14.00	75.11	0.00	0.00	75.11	0.04	0.05	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.63	0.63	75.11
15.00	44.15	0.00	0.00	44.15	0.02	0.03	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.37	0.37	44.15
16.00	24.83	0.00	0.00	24.83	0.01	0.02	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.21	0.21	24.83
17.00	13.37	0.00	0.00	13.37	0.01	0.01	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.11	0.11	13.37
18.00	6.90	0.00	0.00	6.90	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.06	0.06	6.90
19.00	3.41	0.00	0.00	3.41	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.03	0.03	3.41
20.00	1.61	0.00	0.00	1.61	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	12.50	12.51	120.00	119.90	0.01	0.01	1.61

Scenario 14 in Route C

t (h)	Entrance flow	Exit Flow	Carryover	Demand	d/c_HCM	d/c_MKJ	UR_HCM	UR_MKJ	OR_HCM	OR_MKJ	TR_HCM	TR_MKJ	T_HCM	T_MKJ	S_HCM	S_MKJ	D_HCM	D_MKJ	Exit Flow
0.00	141.93	0.00	0.00	141.93	0.07	0.09	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.18	1.32	141.93
1.00	409.15	0.00	0.00	409.15	0.21	0.27	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	3.41	3.79	409.15
2.00	629.65	0.00	0.00	629.65	0.33	0.42	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	5.25	5.84	629.65
3.00	782.14	0.00	0.00	782.14	0.41	0.52	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.99	120.00	107.26	6.52	7.29	782.14
4.00	857.38	0.00	0.00	857.38	0.45	0.57	0.00	0.01	0.00	0.00	0.50	0.57	12.50	14.15	120.00	106.02	7.14	8.09	857.38
5.00	858.53	0.00	0.00	858.53	0.45	0.57	0.00	0.01	0.00	0.00	0.50	0.57	12.50	14.15	120.00	106.00	7.15	8.10	858.53
6.00	798.77	0.00	0.00	798.77	0.42	0.53	0.00	0.00	0.00	0.00	0.50	0.56	12.50	14.01	120.00	107.04	6.66	7.46	798.77
7.00	697.22	0.00	0.00	697.22	0.36	0.46	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.88	5.81	6.46	697.22
8.00	574.40	0.00	0.00	574.40	0.30	0.38	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	4.79	5.32	574.40
9.00	448.43	0.00	0.00	448.43	0.23	0.30	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	3.74	4.16	448.43
10.00	332.68	0.00	0.00	332.68	0.17	0.22	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	2.77	3.08	332.68
11.00	235.00	0.00	0.00	235.00	0.12	0.15	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.96	2.18	235.00
12.00	158.31	0.00	0.00	158.31	0.08	0.10	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	1.32	1.47	158.31
13.00	101.83	0.00	0.00	101.83	0.05	0.07	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.85	0.94	101.83
14.00	62.59	0.00	0.00	62.59	0.03	0.04	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.52	0.58	62.59
15.00	36.79	0.00	0.00	36.79	0.02	0.02	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.31	0.34	36.79
16.00	20.70	0.00	0.00	20.70	0.01	0.01	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.17	0.19	20.70
17.00	11.15	0.00	0.00	11.15	0.01	0.01	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.09	0.10	11.15
18.00	5.75	0.00	0.00	5.75	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.05	0.05	5.75
19.00	2.84	0.00	0.00	2.84	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.02	0.03	2.84
20.00	1.35	0.00	0.00	1.35	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.56	12.50	13.90	120.00	107.91	0.01	0.01	1.35

Scenario 15 in Route C

t (h)	Entrance flow	Exit Flow	Carryover	Demand	d/c_HCM	d/c_MKJ	UR_HCM	UR_MKJ	OR_HCM	OR_MKJ	TR_HCM	TR_MKJ	T_HCM	T_MKJ	S_HCM	S_MKJ	D_HCM	D_MKJ	Exit Flow
0.00	85.16	0.00	0.00	85.16	0.04	0.05	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.76	0.76	85.16
1.00	245.49	0.00	0.00	245.49	0.13	0.15	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	2.18	2.18	245.49
2.00	377.79	0.00	0.00	377.79	0.20	0.23	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	3.35	3.35	377.79
3.00	469.28	0.00	0.00	469.28	0.24	0.29	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	4.16	4.16	469.28
4.00	514.43	0.00	0.00	514.43	0.27	0.32	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	4.56	4.56	514.43
5.00	515.12	0.00	0.00	515.12	0.27	0.32	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	4.57	4.57	515.12
6.00	479.26	0.00	0.00	479.26	0.25	0.29	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	4.25	4.25	479.26
7.00	418.33	0.00	0.00	418.33	0.22	0.26	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	3.71	3.71	418.33
8.00	344.64	0.00	0.00	344.64	0.18	0.21	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	3.06	3.06	344.64
9.00	269.06	0.00	0.00	269.06	0.14	0.16	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	2.39	2.39	269.06
10.00	199.61	0.00	0.00	199.61	0.10	0.12	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	1.77	1.77	199.61
11.00	141.00	0.00	0.00	141.00	0.07	0.09	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	1.25	1.25	141.00
12.00	94.99	0.00	0.00	94.99	0.05	0.06	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.84	0.84	94.99
13.00	61.10	0.00	0.00	61.10	0.03	0.04	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.54	0.54	61.10
14.00	37.55	0.00	0.00	37.55	0.02	0.02	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.33	0.33	37.55
15.00	22.07	0.00	0.00	22.07	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.20	0.20	22.07
16.00	12.42	0.00	0.00	12.42	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.11	0.11	12.42
17.00	6.69	0.00	0.00	6.69	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.06	0.06	6.69
18.00	3.45	0.00	0.00	3.45	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.03	0.03	3.45
19.00	1.70	0.00	0.00	1.70	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.02	0.02	1.70
20.00	0.81	0.00	0.00	0.81	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	13.31	13.31	112.70	112.70	0.01	0.01	0.81

Scenario 16 in Route C

t (h)	Entrance flow	Exit Flow	Carryover	Demand	d/c_HCM	d/c_MKJ	UR_HCM	UR_MKJ	OR_HCM	OR_MKJ	TR_HCM	TR_MKJ	T_HCM	T_MKJ	S_HCM	S_MKJ	D_HCM	D_MKJ	Exit Flow
0.00	85.16	0.00	0.00	85.16	0.04	0.06	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.76	0.84	85.16
1.00	245.49	0.00	0.00	245.49	0.13	0.16	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	2.18	2.42	245.49
2.00	377.79	0.00	0.00	377.79	0.20	0.25	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	3.35	3.72	377.79
3.00	469.28	0.00	0.00	469.28	0.24	0.31	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	4.16	4.63	469.28
4.00	514.43	0.00	0.00	514.43	0.27	0.34	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	4.56	5.07	514.43
5.00	515.12	0.00	0.00	515.12	0.27	0.35	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	4.57	5.08	515.12
6.00	479.26	0.00	0.00	479.26	0.25	0.32	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	4.25	4.73	479.26
7.00	418.33	0.00	0.00	418.33	0.22	0.28	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	3.71	4.12	418.33
8.00	344.64	0.00	0.00	344.64	0.18	0.23	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	3.06	3.40	344.64
9.00	269.06	0.00	0.00	269.06	0.14	0.18	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	2.39	2.65	269.06
10.00	199.61	0.00	0.00	199.61	0.10	0.13	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	1.77	1.97	199.61
11.00	141.00	0.00	0.00	141.00	0.07	0.09	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	1.25	1.39	141.00
12.00	94.99	0.00	0.00	94.99	0.05	0.06	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.84	0.94	94.99
13.00	61.10	0.00	0.00	61.10	0.03	0.04	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.54	0.60	61.10
14.00	37.55	0.00	0.00	37.55	0.02	0.03	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.33	0.37	37.55
15.00	22.07	0.00	0.00	22.07	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.20	0.22	22.07
16.00	12.42	0.00	0.00	12.42	0.01	0.01	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.11	0.12	12.42
17.00	6.69	0.00	0.00	6.69	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.06	0.07	6.69
18.00	3.45	0.00	0.00	3.45	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.03	0.03	3.45
19.00	1.70	0.00	0.00	1.70	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.02	0.02	1.70
20.00	0.81	0.00	0.00	0.81	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.59	13.31	14.79	112.70	101.43	0.01	0.01	0.81

Scenario 1 in Route A

	HCM	WTEC
Entrance flow	1755.25	1755.25
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	1755.25	1755.25
d/c	0.91	1.08
ΔUR [min/km]	0.15	0.00
ΔOR [min/km]	0.00	3.32
TR_{FFS} [min/km]	0.50	0.50
TR [min/km]	0.65	3.82
T_{avg} [min]	3.24	15.69
S_{avg} [km/h]	92.67	15.69
D [veh/km]	18.94	60.15
Demand-capacity	0.00	123.25
Queue length [km]	0.00	2.05

Scenario 1 in Route B

	HCM	WTEC
Entrance flow	1755.25	1755.25
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	1755.25	1755.25
d/c	0.91	1.08
ΔUR [min/km]	0.15	0.00
ΔOR [min/km]	0.00	1.11
TR_{FFS} [min/km]	0.50	0.50
TR [min/km]	0.65	1.61
T_{avg} [min]	9.71	24.12
S_{avg} [km/h]	92.67	37.31
D [veh/km]	18.94	47.04
Demand-capacity	0.00	123.25
Queue length [km]	0.00	2.62

Scenario 1 in Route D

	HCM	**WTEC**
Entrance flow	1755.25	1755.25
Exit Flow t-1	0.00	0.00
Carryover demand	0.00	0.00
Demand	1755.25	1755.25
d/c	0.91	1.08
ΔUR [min/km]	0.15	0.00
ΔOR [min/km]	0.00	0.47
TR_{FFS} [min/km]	0.50	0.50
TR [min/km]	0.65	0.98
T_{avg} [min]	22.66	34.13
S_{avg} [km/h]	92.67	61.53
D [veh/km]	18.94	28.53
Demand-capacity	0.00	123.25
Queue length [km]	0.00	4.32